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A GUIDE FOR THE CONSIDERATION OF COMPOSITE MATERIAL IMPACTS ON AIRFRAME COSTS

THESIS

Jeffrey L. Isom, Captain, USAF

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A GUIDE FOR THE CONSIDERATION OF COMPOSITE MATERIAL IMPACTS ON AIRFRAME COSTS

THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

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Master of Science in Cost Analysis

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Preface

The purpose of this study was to develop a guide to assist analysts in constructing cost models for airframes which have incorporated composites. A literature search was performed to determine what currently available cost estimating models account for the presence of composites. The primary research methodology consisted of a Delphi process used to elicit expert opinion on possible cost drivers, the impact on production hours due to composites, and how composites effects differ across the primary aircraft types.

In the process of constructing the Delphi questionnaire and performing the Delphi iterations I received a great deal of help from others. I am indebted to Mr. Jeff Daneman, my thesis advisor, who displayed a great deal of patience throughout the entire process. I would also like to thank my reader, Ms. Jane Robbins for insightful comments and Dr. Richard Murphy for originally suggesting the Delphi approach when my search for actual data produced few results. Additionally, I would like to thank Mr. A. Michael Welch, and Ms. Donna Rosenbaum of ASD/FMCR for their support, encouragement, and assistance throughout the entire thesis process. Finally, a very special thanks to my wife Pamela for her love, support, encouragement, and incredible patience during my entire time at AFIT.

Jeffrey L. Isom

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Abstract

This study provides a guide to cost analysts who must consider the impact of composite materials on airframe costs. A literature review was conducted to determine the availability of cost models which incorporate the effect of composites on cost. A number of models are available, but no individual model was found that is applicable for every situation. In order to provide a baseline upon which analysts can compare model results as well as provide guidance in selecting cost drivers, a Delphi survey was conducted. Questionnaire results indicate that composite weight (as a percentage of total weight), composite part complexity, percentage of composites in load-bearing role, composite part size, fabrication technique, and percentage of composites in a low observable role are all potentially significant cost drivers. Delphi results also indicate that engineering and quality assurance labor hours are quite sensitive to composite weight, while manufacturing and tooling hours are more sensitive to composite part complexity. Finally, the Delphi results indicate that, although there are some differences in composite labor hour impacts across aircraft type, there are no discernable patterns to the differences.

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I. Introduction

General Issue

The decrease in tension between the United States and the Soviet Union has resulted in increasing pressure to reduce defense spending. At the same time, the expanded use of high technology in weapons systems has given rise to ever increasing costs. For example, the F-4C Phantom II cost about $9.6 million dollars (fly-away cost in constant FY86 dollars) per aircraft while the estimated cost for the Advanced Tactical Fighter (ATF) is $36 million per plane (18:76). A large portion of these cost increases can be attributed to a greater number of onboard and embedded computers for targeting and control as well as ever more advanced avionics systems. However, the rising use of high technology electronics cannot account for the entire impact of technology on cost. A major contributor to increased aircraft cost is the use of composite materials in airframes.

In order to meet the requirements for both lighter weight and higher performance, aircraft designers and manufacturers have relied more heavily on the use of composites. As a percent of total airframe weight, the use of composites has increased from 1 to 2 percent (F-14A and F-16A) in the 1970's to 26 percent (AV-8B) in the 1980's and is

expected to reach 45 to 60 percent (ATF and V-22) in the 1990's (21:I-4). Because of the ability of composites to retain many of the desirable strength and stress characteristics of traditional materials at reduced weight, a more widespread use of composites is inevitable. The drawback, however, is significantly increased costs.

Although more costly than traditional materials, composites provide the means to new advances in aircraft performance that will allow future aircraft to overcome the greater number of enemy weapons (11:76). Reductions in defense spending in recent years and the cancellation of the Navy's ATF program will make it difficult for Congress to fund systems that use expensive composite materials. However, proponents of these composite aircraft say that the United States will be vulnerable without them. Former head of the Air Force Systems Command, General Lawrence Skantze, said that the revolutionary ATF will allow us to dominate the first quarter of the 21st century (18:80). The recent successes of the F-117 Stealth Fighter during Operation Desert Storm help to prove the capability of advanced aircraft and will make arguments against the use of composites more difficult.

Although the use of composites in military aircraft is probably here to stay, members of the Department of Defense (DoD) must justify the costs of these systems to Congress to receive appropriations. The addition of composites to

airframes as well as increased complexity makes it difficult to accurately predict the cost. In the past, early estimates of cost were done using parametric models. These models used the relationship between cost (in dollars or hours) and some performance characteristic such as speed or weight to predict the cost of the weapon system. In order for such a model to be effective, a relatively large database is required. Unfortunately, most of the traditionally used models do not account for the presence of composites or do so insufficiently to provide for a relatively accurate cost estimate. A model which successfully incorporates the use of composites in airframes to provide a pre-production top-down cost estimate is needed. The problem with the traditional approach, however, is the lack of a sufficiently large database of composite aircraft as well as the limited information available on how exactly composites effect cost. In order for cost analysts to successfully create cost models, a more complete understanding of composite cost relationships is required.

Background

In order to fully appreciate the difficulty which composites pose to cost estimators, it is necessary to gain a little understanding in composite technology. There are a great many different composites all with varied materials, manufacturing methods, and physical characteristics and the

number continues to grow. For example, there are over 300 types of graphite/epoxy composite materials (22:II-21).

Composites are different from traditional materials because they contain two or more materials joined together to produce specific performance characteristics. The entire technology of composite material is "...based on the controlled distribution of one or more reinforcement materials in a continuous matrix phase (14:53)." Physical and performance characteristics are obtained based not only on the reinforcement material and the matrix, but the way in which they interact.

Reinforcement Materials. Reinforcements come in a variety of forms, but are primarily categorized as: fibers, whiskers, flakes, or spheres. Each form offers unique characteristics to the composite such as strength and stiffness with carbon fibers, toughness with ceramic whiskers, or control of heat expansion with silicon-carbide (5; 14:56-57; 10:36-42). In whatever form, it is the reinforcement which provides the structural characteristics to the composite.

Although the applications for all forms of reinforcement are growing, fibers still dominate the aerospace industry. Fibers are typically woven into fabric, braided into tubes, or preformed into a three-dimensional weave (33). A common raw material form for fiber reinforcement is unidirectional tape. Fiber composites first appeared in the 1940's with

fiberglass, followed by boron fibers in the 1960's, and graphite fibers in the 1980's.

Though Boron was used in the F-14A as the first major aerospace application, graphite/carbon fibers have become the primary fiber used in aerospace composites (10:36-39; 21:I-4--6). Even though graphite/carbon fibers do not offer the absolute strength of boron, they are easier to work with, have higher elastic properties, can be combined with a greater range of matrices, and are less expensive.

The effect a reinforcement material has on the overall composite is predominately a function of three factors: length, orientation, and volume fraction (31:17). Length actually refers to the aspect ratio (length-to-diameter) of the fiber. In general, the reinforcement effect increases as aspect ratio increases. Orientation refers to the manner in which fibers are aligned with applied loads. Alignment of the fiber with applied loads is more effective than random orientation. Finally, volume fraction, is the percentage of total volume made up of reinforcement material. For example, a typical volume fraction for graphite/epoxy is 0.6 and consists of 60% fiber and 40% matrix (31:17).

Matrix Materials. The matrix not only provides the bulk form for the composite, but helps to protect the often brittle reinforcement from abrasion or environmental corrosion. Additionally, the matrix helps to distribute the longitudinal loads carried by the reinforcement (14:54).

Since the matrix material is generally weaker in terms of stiffness and strength than the reinforcement, the matrix determines the mechanical, chemical, and thermal limits of composite (31:22). Currently available matrix materials include organic (or plastic), metal, carbon, and ceramic materials.

<u>Polymer Matrix Composites (PMC)</u>, often called organic/plastic matrices, are the most common matrix material used in aerospace systems. This type of matrix is most often used with graphite fiber/carbon fibers and offers relatively high strength, light weight, fatigue resistance and can withstand moderately high temperatures (7:366). Organic matrix composites have already been used on such aircraft as the B1-B, F-15, F-16, and EF-111 and will probably be used extensively in the new C-17. PMCs are broken into two categories called thermosets and thermoplastics.

Thermosets, utilizing epoxies as the matrix material, have been in use for over 20 years . The strengths of thermoset composites originate from chemical reactions which take place during the cure cycle. This need for chemical reaction results in long cure times, reduces the length of time the composite can be stored, and prevents reforming once the material has been cured. Thermoset composites are usually dimensionally stable, temperature resistant, and solvent resistant (31:23).

Thermosets, in general, are fairly strong, but are sometimes susceptible to degradation when exposed to water, hydraulic fluid, jet fuel, or cleaning fluids (33). The primary weaknesses in epoxy thermosets are relatively low temperature tolerances and toughness (meaning brittle). It is possible to improve the toughness of epoxy thermosets, but usually only by trading off tensile strength (15:44). Concern over these properties lead to the development of bismaleimide and polyimide thermosets.

Bismaleimides (BMI) have a lower processing temperature than polyimides, but retain much of the heat tolerance capabilities except at the very high-end range (13:60). Although polyimides do exceed bismaleimides in temperature tolerance, they must be processed at temperatures high enough to require modifications in typical autoclaves, while BMIs can be cured in the same facilities as epoxies. The primary problem with polyimides are the greater costs and relatively recent entrance into the production arena.

Thermoplastics are the second general type of PMC. Development of thermoplastic composites began in the early 1980's in an effort to overcome the inherent weaknesses of thermosets. Thermoplastics have the potential for much higher damage tolerance (toughness), improved microcrack resistance, negligible moisture absorption, and high flame resistance (15:43). Additionally, since thermoplastics require no chemical reactions, they offer an unlimited shelf

life, no necessity for cold storage, and are meltable and reformable (33). Because of the basic properties of thermoplastics, they are much easier to repair and quicker to manufacture than thermosets. However, there are currently a number of problems which are preventing a wider use of thermoplastics as opposed to thermosets.

Current composite manufacturers have factory setups geared toward production and use of thermosets. Since thermoplastics require a great deal more heat and pressure to manufacture, a large capital investment and factory changeover would be required to switch from thermosets to thermoplastics (31:25-26). Further, more labor is involved in laying-up of thermoplastics since they are often stiffer, less tacky, and are difficult to form. Finally, the lack of experience and a historical database of properties make it economically risky to switch from well known thermosets to thermoplastics.

Although a great deal of research is being devoted to thermoplastics, it will be some time before they are used with the frequency of thermosets. New manufacturing methods which reduce the time and temperature requirements are being developed. However, current uses of thermoplastics are usually limited to secondary structure applications (31:28).

Metal Matrix Composites (MMC). MMCs are becoming the center of attention in advanced materials technology. The high interest in MMCs can be ascribed to high strength,

reduced weight, damage tolerance, and their ability to withstand temperature extremes without changing dimensions (33). These properties offer a wide range of application in the space industry as well as in areas such as turbine or compressor blades in jet engines. Additionally, due to their isotropic nature once they are formed, MMCs can often be treated the same as traditional metal during secondary working (5:27).

Metal matrix composites require complex fabrication processes and are currently very expensive to produce (33). However, current plans for the Advance Tactical Fighter include the testing of four vertical tail structural boxes made of silicon carbide reinforcement in an aluminum matrix (31:29).

Carbon/Carbon Composites. The unique characteristics of carbon matrix composites make them suitable for a wide range of potential aerospace applications. Carbon-carbon composites can withstand temperatures beyond those attainable by ceramics and demonstrate increases in strength at these high temperatures. Typical carbon-carbon composites are about two-thirds as strong as superalloys, but increase in strength at high temperatures where the alloys begin to lose strength (25:27). Carbon/carbon composites also offer good resistance to thermal shock and have good thermal and electrical conductivity (33).

Carbon matrix composites often use graphite (a form of carbon) as reinforcement material which not only gives the composite a high degree of strength, but allows sliding against other components with no galling. This property gives rise to the use of carbon-graphite composites in applications such as aircraft brakes, where reductions in weight and increased time between repairs have been demonstrated (25:31). Although carbon/carbon composites have been in use for twenty five years, they are only now being studied for application in aircraft structures (33). Currently, the use of carbon matrix composites is limited because of long and expensive manufacturing processes.

Ceramic Matrix Composites (CMC). A relatively recent entrant into the advanced materials arena, ceramic matrix composites offer high temperature applications. Unlike other composites, the strength of ceramic composites is controlled by the failure strength of the matrix rather than the reinforcement (5:27). Although a great deal of research and experimentation is being conducted on ceramic matrices, problems in the interface area, brittleness, and matrix chemistry have resulted in limited application.

CMCs have a great deal of potential, however, because they offer superior wear resistance, high temperature strength, and chemical stability compared with metals. The two primary obstacles to widespread use of CMCs are: the development of high strength continuous fibers which are not

degraded by ceramic matrix processing or operating conditions; and fabrication processes which do not result in microcracks or degraded aligned fibers surrounded by a porous matrix (31:39-30).

Fabrication. Although the reinforcement and matrix are critical in determining the properties of a composite, the manner in which they are arranged is just as vital (14:57). Composites are formed by introducing the reinforcement material, in whatever form, into the matrix. Particular fabrication methods are governed not only by the types of materials used as reinforcement and matrix, but by equipment requirements and the desired composite properties. There are a great many fabrication methods and each offers specific benefits and drawbacks.

Fabrication techniques and cost are generally driven by design considerations. Primary structures are flight critical and must be able to endure high loads, fatigue, and environmental effects. Therefore, primary structures tend to be more expensive, since more exacting fabrication techniques as well as higher quality materials must be used (31:42-43). Secondary structures, on the other hand, are not as flight critical, do not carry primary loads, and therefore may not require the more expensive materials and fabrication methods.

The size and shape of composite parts also have an impact on the fabrication technique. Very large or highly contoured parts can only be fabricated using two of the

currently available techniques. As part size and complexity are reduced, more fabrication techniques become viable and relative costs can be expected to go down.

Before fabrication begins, composite materials are usually purchased in a "prepreg" or "preform" state. Prepregs are reinforcement materials (usually tape, fabric, or broadgood) which have been pre-impregnated with liquid matrix material and precured to a viscous state (31:138-139). Preforms are reinforcement and matrix material combined into a predetermined configuration prior to actual fabrication. Basically, prepreg is the organic matrix composite equivalent of the more general term preform. From the preform state, there are a number of steps the composite must go through before a part is completed.

Tooling. Tooling costs for composites are usually higher than for metal. One of the drivers of increased tooling costs is the strict tool tolerances required in composite manufacturing. Tools for metal parts do not have the need for high tolerance, because excess material can be tooled to fit specifications (31:47).

Probably the primary cost driver for tools is the mismatch in thermal expansion between composite and tool. Since the typical composite requires relatively high temperature curing, both the composite and the tool endure prolonged exposure to high temperatures. Differences in thermal expansion between the tool and the composite can

result in damage to both (31:47). Therefore, thermal differences must not exceed levels where part warping is acceptable.

Potential remedies for thermal differences include the use of composite tools or more sophisticated tool design. Unfortunately, composite tools are a great deal more expensive than their metal counterparts. More sophisticated tools use analytical models to locate potential trouble spots in the tool before actual use (31:48). Tools can then be modified to minimize potential damage, but this can also increases tooling costs.

Hand or Automated Lay-up. Before lay-up procedures can begin, the composite material must be cut into patterns. Usually, several layers (plies) are needed for each part. Manual cutting of plies, although very slow and expensive due to high labor costs, is common for small to medium sized complex contoured parts (31:49). Automated pattern cutting is done using Gerber knives, waterjets, lasers, or chisel cutters. Automated cutting is a great deal faster than manual cutting and is usually more accurate. Although the use of automated pattern cutting reduces ply inconsistencies and inspection requirements, equipment costs are high. Automated cutting is usually reserved for large, multi-layer patterns or where a large number of parts are required.

Once the patterns are cut, each ply is laid-up and oriented in the tool as predetermined by the design. The

lay-up procedure is the largest cost driver of all composite labor costs (31:49). Costs are driven by the need for precisely controlled fiber alignment. For example:

> ...continuous, parallel fibers may provide high strength in the direction of fibers, but offer very low transverse strength. Adding a 90^0 crossply will provide fairly high strength in the 0 and 90^0 directions, but the composite will be weak at 45^0. Using 120^0 triple plies will supply moderate strength in roughly all directions. If fibers are discontinuous, or if they are not parallel, strength may be reduced by an order of magnitude. (14:57)

Hand lay-up, currently the most common method, is the simplest technique. Although labor intensive and quite expensive, this method allows a great deal of flexibility in design and a minimum in equipment investment.

In hand lay-up, the reinforcement is placed in a mold in the desired configuration and the matrix is applied by pouring, brushing, or spraying (14:54). Lay-up of material is a complex and exacting procedure and tends to be time consuming and error prone. Mistakes are extremely likely whenever more than 20 separate plies must be formed (31:50). Unfortunately, many parts exceed the ability of currently available automated procedures and must be accomplished manually.

Tape lay-up on mildly contoured parts can often be automated. For parts where automation is possible, the lay-up process is much faster and the plies are laid in such a manner that debulking is not required. Debulking is the process through which plies are compacted to eliminate gaps

in the laminates so the part will fit properly in the tool. New programming tools are no becoming available which will increase the compatibility between parts and tape laying machines (31:50). The major drawback to automation is the high equipment costs. Therefore, automated lay-up is most practical for similar parts produced in large numbers.

Other Lay-up Techniques. Some additional methods for laying-up composites are filament winding, pultrusion, and braiding. Filament winding is done by feeding filament or narrow prepreg tapes through a resin bath and winding them on a male mandrel (14:55). The process is automated and very cost effective for shapes with no concave curvatures (33). Filament windings offer a very high strength-to-weight ratio over other lay-up methods.

Pultrusion is useful for producing straight parts with a constant cross section. Dry fibers are pulled through a liquid matrix and then through a heated die which shapes the part and pre-cures it (31:60;33). Pultrusion is very cost effective, but somewhat limited in flexibility. This method produces very high strength parts due to the high fiber concentration and alignment (14:56).

Braiding can be used for parts with long, continuous lengths and simple cross sections (31:59). A reinforcement preform is impregnated with a matrix material and braided into a multidimensional configuration. Thickness and fiber direction can be adjusted to give greater damage tolerance to

the part (31:59). Although an alternative to traditional lay-up procedures, braiding is also labor extensive and therefore fairly expensive.

<u>Curing</u>. After lay-up, most composite parts require curing through temperature and pressure though some can be cured at room temperature. The most common method for curing composites is the autoclave. Parts are bagged and sealed in a vacuum bag which keeps pressure on the laminate and forces against the forming tool. Loss of vacuum seal is the most prevalent cause of scrapped parts in composite fabrication (31:51).

Once sealed in the vacuum bag, the part is placed in the autoclave for a prescribed length of time at a set temperature and pressure. Curing processes the composite to its final hardened state. Thermosets are often postcured in ovens for several hours in order to achieve the maximum crosslinking and strength in the matrix (31:52). Thermoplastics do not require the chemical reactions necessary for thermosets. They are said to consolidate rather than cure and require much higher temperatures than thermosets. Autoclave curing generally results in higher densification and greater reinforcement than other methods, but autoclaves are very expensive (14:56).

Curing with just the vacuum bag and an oven is also possible. However, the only pressure provided by a vacuum bag is atmospheric pressure. Therefore, densification and

reinforcement are substantially less than in an autoclave; but costs are reduced (31:59).

Thermal expansion curing utilizes the differences in expansion between materials to provide pressure. Plies are wrapped around a mold which is placed in a metal cavity and heated. The mold is constructed of a material which expands at a rate faster than the metal of the cavity. As heat increases, the expanding mold forces the composite plies against the metal cavity creating pressure. This method is relatively inexpensive, but the design must be precise enough to provide the proper amount of pressure (31:59).

Other Fabrication Techniques. Almost all composites must be cured to an extent. However, there are several techniques which combine the more traditional ply cutting, lay-up, and cure cycles into one process. Consolidated fabrication techniques generally require much less time, but involve varying degrees of expensive equipment. Additionally, many of these techniques are limited in the types of parts they can produce.

Injection molding is fairly expensive, so a large number of parts are needed to make it cost effective. The process involves injecting a mixture of matrix and reinforcement into a mold where heat and pressure are applied. This process is useful for both thermoplastics and thermosets and can produce very complex parts (14:57).

Compression molding is fairly flexible and can produce larger parts than injection molding, but is fairly flexible as far as part complexity (14:56). The matrix and reinforcement materials (usually a preform with resin added at the press) are placed in a heated mold cavity and subjected to high pressure using a hydraulic press (31:60). This technique can be used with both thermosets and thermoplastics as well as many others.

Resin-Transfer molding can produce very large parts with a high degree of reinforcement (14:57). However, maintaining fiber alignment is difficult and often labor intensive. Fiber mats or preforms are usually used and must be oriented properly to assure fiber alignment. Once the preforms are in place in the mold, the mold is closed and filled with low-viscosity resins and heated until cured (33).

Fabrication Summary. The important differences in fabrication techniques are the varying degrees of touch-labor versus machinery required, the characteristics of the resulting interface, and the part size or design limitations inherent in the technique. The differences in fabrication methods often result in trade-offs between cost, capital equipment out-lays, and the desired performance characteristics of the composites.

Specific Problem

The almost limitless materials which can be used as reinforcements and the availability of numerous matrix materials and fabrication techniques make reliable cost estimating an almost impossible task. This problem is especially apparent early in a program's life when detailed requirements and technical specifications are not available. Additionally, since composites are a relatively new phenomenon, there is little actual knowledge on the costs of production for most of the newly available composites.

The relationship between metal and composites in an airframe, manufacturing and fabrication methods, as well as part size and complexity all impact on cost. Before an effective model can be constructed, a good working knowledge of the interactions between these "cost drivers" must be obtained. The DoD needs a reliable guide which can aid the modeler in determining the appropriate estimating methodology as well as providing a results check for potential models.

Research Objective

The objective of this research is to provide a guide for cost modelers which will identify some potentially significant cost drivers which can account for the presence of composites in airframes as well as explore some of the interactions between them. Additionally, the guide will provide a

reference for the expected cost impacts for various combinations of these cost drivers.

Investigative Questions

Answers to these questions will provide the means to fulfill the research objectives:

1. What are some of the available cost estimating models which can be used as predictors of airframe costs when composites are involved?

2. One of the most common traditional CERs uses cost (usually in hours) as the dependent variable and weight (the size variable) as the independent variable. Is there still such a relationship for metal-composite airframes?

3. Are there other significant cost drivers which account for the differences bwtween composite and metal airframe costs?

4. If there are other significant cost drivers for metal-composite airframes, are the relationships increasing or decreasing?

5. How do various combinations of cost drivers effect the cost of an airframe in terms of labor hours for the different labor categories?

6. Do these combinations of cost drivers behave in the same manner across aircraft type (e.g. fighter, bomber, tanker)?

Scope and Limitations

Detailed and accurate cost data is not readily available, especially for either very new or very old programs. Furthermore, the ability to analyze the effect of composites on aircraft procurement cost is hampered by lack of actual data, widely varying material types and manufacturing methods, and inconsistent data formats and cost tracking procedures (21:I-1). Therefore, this research will be limited to an over-all airframe level rather than lower WBS levels.

Although there are a great variety of composite materials available, graphite and boron composites dominate current aerospace applications. Additionally, though newer aircraft may indeed use composites other than graphite or boron, little production data is available and the addition of one or two data points would offer very little in the way of model validity. Therefore, for the purpose of this thesis, only graphite and boron will be considered when searching for composite cost drivers.

Finally, this research is directed towards providing a guide for analysts to aid in the construction of weapon system specific cost models or modification of existing models for a specific purpose. As such, the guide will be useful primarily early in a programs life when little actual data is available for estimating purposes. The guide will provide the analyst with a brief synopsis of generic models currently available, possible cost drivers, and the expected impact on production

hours for various combinations of these cost drivers. This guide is not designed as a definitive composite cost estimators handbook, but rather as a starting point from which to begin constructing a model which must consider composites.

II. Literature Review

Introduction

Most parametric cost models use regression analysis to determine the relationship between cost and various cost drivers. Usually, cost drivers take the form of one or more performance parameters, such as weight or speed. Prior to the use of composites, models developed based on these parameters were relatively successful as rough order of magnitude estimators (20:2). However, the increasing complexity of aircraft and the use of composites has seriously degraded the reliability of formerly useful models.

The need to account for composites in cost estimating has been recognized and several models which attempt to do so have been developed. Three major problems in developing such a model are: 1) the great variety of composites and manufacturing methods, 2) the relatively small composite aircraft database, and 3) the as yet unexplored interactions among the potential cost drivers. The difficulties posed by these problems have arisen repeatedly during a review of the relevant literature.

Various solutions to the above problems have been proposed by a number of sources. A variable which adjusts for the passage of time is a potential method for dealing with the increased complexity and use of composites in more recent aircraft (24:14). Another suggestion has been to include

indicator variables for the manufacturing methods and a technology variable to account for increased complexity (20:5). Rather than addressing composites directly, these methods proceed under the assumption that cost models can be improved simply by incorporating cost drivers other than performance and size. It should be noted at this point, however, that a study prepared for Assistant Secretary of Defense for Program Analysis and Evaluation concluded that the addition of any of the above variables offers little hope for improving parametric models over those using only speed and weight (24:53).

The most common, and currently most often used, methods for dealing with composites involve modifications to existing models, discrete models for composites only, and parts-up models using factors which attempt to equate aluminum parts to their equivalent in composites (21:III2-5; 23:15-33). Although models using the factors approach are not "pure" parametric models, regression analysis is often used to determine the aluminum equivalent costs. The major drawback to using factors in order to estimate composite costs from their equivalent aluminum counterparts is the assumption that each airframe structure is of equal importance. However, according to research done by Management Consulting & Research, Incorporated (MCR), the location of the composite structure on an airframe is an important determinant of costs (22:II-25).

As long as the factors approach is used on a part-for-part basis, the results should be fairly valid. However, this assumes that the estimator has data on both aluminum and composite production for each part. It is erroneous to assume a consistent relationship between composites and aluminum for all parts. For example, there is typically a range of 5 percent to 40 percent weight savings, from aluminum to composite, depending on airframe structure (22:II-25).

There are a number of models currently available to estimate the cost of airframes which utilize composites. There are also a number of models developed by aircraft manufacturers, but by and large these models are proprietary and not available to the government analyst. Models vary in both approach and usefulness during various stages of a program's life. In general, a generic model must be modified for any specific application and no model should be considered a panacea for all airframe types.

ACCEM

The Composite Cost Estimating Method (ACCEM) was developed by Northrop primarily for estimating the cost of composite piece parts in the 2 to 35 pound range (21:III2). The model was developed in 1976 and therefore does not contain data which reflect more recent composite technology. ACCEM is a computer model which uses a Work Breakdown Structure (WBS) approach to estimate the cost of individual parts.

Because of the WBS approach, a great deal of detailed information is required and running the model can prove extremely tedious. After using the model to compare predicted values with actuals for the F-14 horizontal stabilizers, Grumman Corporation concluded: "The ACCEM program in its present configuration is too laborious to use in detail design, and not suited at all for preliminary design (30:54)." Additionally, the Grumman report indicated that ACCEM estimates averaged ten percent low for graphite/epoxy parts and forty percent low for fiberglass/epoxy parts (22:II-23).

FACET

Also developed by Northrop, the Fabrication Cost Estimating Technique (FACET) is basically a modified and enhanced version of ACCEM. FACET was developed in 1979 and, while more current than its predecessor, is still sufficiently dated to warrant caution when used for estimating in the current technological time frame. This model also deals mostly with composites on a parts level and includes a database consisting of 244 composite material parts manufactured by 24 companies (34:17-27).

FACET deals mostly with pre-production programs and is not well suited for a top-down estimating approach since detailed parts lists are required. Additionally, the model cannot be used by itself to estimate airframe costs since parts must be summed from the bottom up and metal parts are

not included as an output. However, FACET does provide one of the better parametric estimators at the part level (23:18). Testing has indicated that FACET averaged about a ten percent cost difference for eight composite components when compared with actual data (22:II-23). Therefore, if detailed information is available, this model can be used in conjunction with one or more other models to provide a fairly useful estimate.

MLCCM

Developed by the Grumman Corporation, the Modular Life Cycle Cost Model (MLCCM) uses separate cost estimating relationships (CERs) for the airframe, engines, and avionics. This model was developed in 1980 and, unlike most available models, can be used for R&D, Production, and O&S costs. The CERs were built to work at a WBS level and require fairly detailed design information such as wing chord, internal fuel capacity, and wing area (21:III4). The model accounts for advanced manufacturing techniques and materials by way of factors. The factors are tooling, labor, and materials and are based on costs for aluminum (16:74). The model estimates the cost of an airframe as if it were all aluminum, and the factors are then applied where appropriate.

Besides the disadvantages to a factors approach mentioned previously, an additional drawback to this model's factors is that they were developed by polling industry experts and

averaging the responses, rather than using a more objective method. Although the use of expert opinion may be quite useful in an area of emerging technology such as composites, the age of the model tends to limit credibility. The usefulness of this model could be greatly enhanced simply by updating the factors.

DAPCA IV

Probably the most widely used model for estimating aircraft costs early in a program's life, the Development and Procurement Costs of Aircraft (DAPCA) model is an evolutionary model with the latest version being DAPCA IV. The model was developed by Rand Corporation during the 1960's and updated in 1983 to include indices which account for the presence of composites (23). A further update, to DAPCA IV, was published in draft form in 1988.

DAPCA IV is an improvement over its predecessor, DAPCA III, in several areas. First, the database has been substantially expanded to include the A-10, F-15, F-16, F-18, F-101, and S-3 (27:1). Secondly, the computer version is interactive in nature as opposed to batch entry. Finally, since most current aircraft production numbers are relatively small, learning curve slopes revolve around unit one rather than unit 100 as in DAPCA III (27:1).

The model is parametric in nature and uses speed and weight as independent variables. Total airframe cost is the

output and is broken down into engineering, quality control, manufacturing, and tooling hours along with material cost (2:6). The final output cost is based on a regression equation which takes into account cost-quantity slopes for the applicable labor category. The output is then multiplied by a complexity factor and a fully burdened labor rate to arrive at the dollar cost estimate (27:6-18). Care should be taken in selecting a complexity factor since it is subjective in nature and has a multiplicative effect on the results. It may also be advisable to substitute the labor rates for specific contractors and/or subcontractors involved in a program for the generic rates provided in order to tailor the output to that particular program.

The main drawback to the model is the relative age of the composite indices (1983), if used, and the fact that the indices were not based on actual production data, but data which was manufactured using selected representative metal and composite parts. In addition, although updated to 1988, it is advisable to estimate only within the database. It is probable that airframes containing a large percentage of composites will fall far enough outside the database so that even very large complexity factor adjustments may prove inadequate.

Advantages to this model are the excellent documentation available and ease of computerization. Although the indices are somewhat dated and the database limited in composite

aircraft, the database is probably the most comprehensive available and the extensive documentation allow relatively easy updating as new data becomes available.

MCR Model

This model was developed in 1987 and updated in 1990. Following a review of the various models available, Management Consulting & Research, Inc. developed their own model.

> The primary focus of the composite airframe model is on direct manufacturing labor hours and material cost. Other labor hours such as tooling, quality assurance and engineering were modeled as factors of direct manufacturing hours. (21:III7)

The resulting model is especially suited to estimating program costs at the very earliest stages of a program.

The complete model contains CERs for the airframe as a whole, wing, fuselage, empennage, metal fabrication, composite fabrication, and composite assembly (21:IV). The final report contains tables with typical learning curves slopes for various structures and manufacturing elements. Additionally, the report provides tables for buy-to-fly ratios for common materials as well as raw material costs. Finally, factors for non-recurring engineering and tooling hours per pound are provided for major structures as well as for total airframe.

The primary problems with this model are the limited database upon which it was built, the fact that each CER was not developed using the same database, and the questionable

accuracy of some of the labor hours used as data points. Since the model's CERs were based on data of which all but one data point was comprised of fighter or attack aircraft, this model should not be used to estimate bomber or cargo type airframe costs. Additionally, the authors recommend that the model's CERs be refined with any new available data before being used for any specific application (22:III-8).

The advantages to this model are similar to those of DAPCA IV. The model is well documented, relatively easy to use, and easily updated for to reflect additional data. This model is especially suited for trade-off studies very early in a program's life. Tables containing typical weight percentages (of total weight) for primary airframe structures, learning curve slopes, material buy-to-fly ratios, and other difficult to find information is available in the final report and could prove very useful even if the model itself is not used.

Advanced Fighter Aircraft Cost Model

This model was specially designed as an estimating tool for next generation fighters and attempts to incorporate the cost differential due to emerging technology. The model can be run on computer or done by hand and uses a modular approach to estimate airframe, propulsion, avionics, and O&S. An additional module provides for integration for other acquisition costs. The model's final module is used to sum

the appropriate costs from each individual module and computes the aircraft's life cycle cost (1:1-2).

The airframe module produces output at level three WBS for both production and FSD and is based on DAPCA III. Although primarily a parametric model, several adjustments are made to the regression results to obtain the final output. Additionally, the DAPCA III equations have been modified to reflect differences in weight between advanced and conventional structures; impacts on engineering, quality control, tooling, and flight test due to advances in technology; and adjusted to reflect differences in material mix for advanced versus conventional structures on manufacturing labor and material (1:3).

Output from the modified equations described above are adjusted a final time to reflect the overall impact of technology. The technology adjustment factors are intended to reflect the presence of emerging technologies such as computer aided design and manufacturing (CAD/CAM), automation, and so on. These factors are subjective in nature and are based on inputs from local experts. The factor for signature reduction technology is selected from a set of four generic levels of signature reduction developed primarily from contractor data.

The primary drawbacks to this model are similar to the previously described models. The database is somewhat limited and outdated. Adjustments to the database are based

on conversion of actual weight to equivalent weight using equations developed using a 1983 study by Boeing rather than actual data for airframes. Additionally, many of the factors are based on historical trends or "typical" conditions in the current industry which may or may not reflect actual conditions for a specific program. Finally, the subjective nature of the technology factors could have a negative impact on accuracy.

The advantages to this model are essentially those of DAPCA III with a few additions. The model is designed specifically for use on computer and disks are readily available. The model is extremely comprehensive in addressing areas of potential impact due to advances in material and technology. Lastly, although subjective, the technology factors allow the model to be tailored to a given contractor or subcontractor for a specific program rather than relying on the aforementioned generic adjustments.

Military Tactical Aircraft Development Costs

As opposed to the previously discussed models, this model is simply a part of a much larger study. The study itself deals with both past and current aircraft and their subsystems. The study, as a whole, consists of five volumes with the first volume being a summary report. Also different from the other models discussed, this model deals specifically with the costs associated with FSD. Even if the

model contained in the report is not used, the report contains a wealth of information that could prove very useful to the analyst.

The airframe model contained in this report is a parametric model. Since the report is more current than other models discussed, the database used to develop estimating equations is fairly up-to-date. The main difference between the equations in this model and others is the use of two additional variables besides weight and speed. To take into account advanced materials, a variable consisting of percent of airframe structure weight made up of titanium, advanced composites, and aluminum honeycomb was used in place of the more traditional variables of composite weight and metal weight. The other unique variable represents the extent of program development efforts carried out by other than the prime contractor (19:39).

The primary drawback to the model is the difficulty in tailoring results for specific needs. The only variable that can account for contractor peculiarities is the integration variable. Other than one adjustable variable, any modifications require additional airframe data points.

Advantages of the model are the wealth of information available in the report as a whole and the fairly current database upon which the model is based. Since the study was not intended as a stand alone model, it serves its primary purpose as a source of information quite well.

Advanced Aircraft Structures Cost Study

This study was conducted in support of the Advanced Tactical Fighter program office (17:1). Although not technically a model, the study can be quite useful in constructing cost models for advanced technology airframes. The study provides a listing of cost drivers associated with composites and the probable impact on production. Additionally, the study outlines a recommended estimating methodology. Finally, the study includes a database, based on the Rand database and inputs from various contractors, that contains the most up-to-date information available on advanced materials including composites.

A LOTUS spreadsheet was also developed utilizing the estimating methodology contained in the study. There are four versions of the spreadsheet. Version one uses only sizing slopes to estimate both dollars and hours, version two use both sizing slopes and factors, versions three and four are essentially the same as one and two, but are based on projected costs for 1995 (17:8). Essentially, the spreadsheet uses sizing slopes to relate cost parameters to input weights and then computes cost by material type and function for both simple and complex structures. Calculations are normalized to 1000 pounds Airframe Unit Weight (AUW) and do not include final checkout and assembly (17:9). Results are total labor hours and unburdened material dollars.

The only major drawbacks to the model are the necessity for extremely close cooperation with the technical community and the questionable validity of the 1995 cost projections. Many of the required inputs require "educated guesses" since early in the program the required information may not be available. Additionally, the estimated costs for 1995 were based on applying the average ratio of differences between 1988 and 1995 costs to the 1988 data set. Ordinarily, this might not be a problem. However, there was no difference in some of the costs, and the factor was based only on those costs which had differences.

Advantages to this approach are the availability of easy to use spreadsheets, the fairly extensive database, and the ease with which the approach can be adjusted for a particular program. Since the study is not truly a model, the methodology can be used for practically any application with modifications made to fit the requirements.

<u>Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology</u>

This model is also parametric in nature and applies weighted materials indexes to the results obtained from regression equations using weight and speed as independent variables. The materials indexes were based on a fairly comprehensive industry survey and include factors for late 1980's and mid 1990's. Model output is in 1990 dollars and provides estimates for: non-recurring engineering and

tooling; development support; flight test; recurring engineering, tooling, quality assurance, manufacturing labor and material (31:105).

Unlike most factor approaches, this model provides separate CERs and materials indexes for each cost element. Additionally, sizing slopes and learning curve slopes are provided to tailor output for specific uses. Finally, the weighted indexes are built up based on cost element, material cost and buy-to-fly ratios, and structural complexity factors (31:105-109). This approach allows for a great deal of flexibility when applying the model.

The model supplies a great deal of useful background information as well as potential impacts due to a changing technological environment. The dollars per pound figures for recurring cost elements as well as the ratios for non-recurring cost elements are provided in the documentation. An average value as well as minimum and maximum values for each material type involved in the study are provided for each ratio and dollar per pound value. All ratios and dollar per pound values are based on cumulative average costs for 100 units for 1000 pounds of structure (31:82-99).

The primary drawback to this model is in the construction of the material indexes. Dollars per pound values and non-recurring cost ratios are based on the average of the average values received in the industry survey rather than a consensus. In many cases, especially in the recurring

cost elements, the ranges of values are quite large and lend little credibility to the averages. The only other drawback, the accuracy of mid 1990's projections, is reported by the author. During the time frame of the industry survey, the defense contracting environment permitted a good deal of optimism. The current environment, however, may reduce: the quantities of materials purchased, the anticipated gains in experience in working with advanced materials, and outlays for automation and capital equipment. These reductions may serve to significantly lessen the cost reductions anticipated by the mid 1990's (31:94).

The advantages to this cost model are numerous. The CERs are based on the most current information available, are well documented, and are easily applied. While also a potential drawback, the range values given for the various cost elements are accompanied with possible explanations for the variances. These explanations allow the manager some insight into how a particular factor could be tailored for a specific situation. Further, the indices permit a great deal of flexibility in application. Finally, the manner in which the weighted material indices are computed is a considerable improvement over the more typical indices found in many models.

Summary

This chapter summarizes some of the many problems analysts face in attempting to model airframes which utilize

composite materials. In response to investigative question 1, the chapter presents a brief guide to currently available composite airframe cost models. A brief synopsis of the primary features, estimating technique, potential weaknesses, and possible advantages for each model is included.

The analyst should keep in mind, however, that both advantages and disadvantages for any given model are highly dependent upon the circumstances of its use. No single model is the best alternative for every situation. In many instances, a combination of several models may provide the best estimating methodology. The purpose of this chapter is simply to make the analyst aware of some of the tools that are available. Chapter three describes the methodology used to answer the remaining investigative questions.

III. Basic Methodology

Introduction

The objective of this research was to develop a guide for analysts as they construct cost models which must account for impact of composites on airframe costs. The most obvious starting point in terms of potential cost drivers is the relationship that exists between cost and weight for aircraft. According to Maj. Ronald Decamp and Maj. David Johnson, weight is the only engineering parameter that demonstrates a clear cut trend in relation to the cost of historical aircraft (9). Although some of the better parametric models use speed as an additional cost driver; recent aircraft such as the F-111 and B-1, which are both heavy and fast, could reduce the significance of speed as a cost driver.

A review of the relevant literature indicates that part size and part complexity are also potentially significant cost drivers. Part size, especially as size becomes very large, tends to increase the capital equipment requirements (e.g. large autoclaves) needed to manufacture the part. Part complexity tends to drastically increase the touch labor required as well as increasing the scrap potential. An additional consideration is the possibility that complex metal parts are not replaced by composite parts. Rather, several metal parts are often replaced by a single complex

composite part. The results in such a situation would be a combination of both complex metal and composite parts, thus increasing the overall labor requirements. Increases in capital equipment or touch labor usually result in higher costs.

An additional potential cost driver is the amount of composites serving in load-bearing roles. Initial uses of composites in aircraft were merely for the weight saving benefits. As composites were more fully developed, the greater potential in other areas was recognized. In the future, composites will be seen in almost any part of an aircraft structure. However, it is possible that the additional hours required to design and manufacture composites which are able to withstand the tremendous loads encountered during flight could result in much higher costs than for a metal equivalent.

The final potential cost driver considered is the use of composites for the purposes of low observability. As opposed to common belief, composite materials are not inherently low observable by nature. Many composites are somewhat translucent to radar, which allows reflection from within a composite structure. Therefore, only by special design and additional effort are most composites imbued with the necessary electrolytic characteristics necessary for low observability. Increases in material, design, and

manufacturing costs would probably result due to the use of composites in a low observable role.

Other potential cost drivers not considered in this research are types of composite (matrix and reinforcement material) and manufacturing method. Increases in the use of automation are expected to decrease the cost of composite manufacturing. However, currently the vast majority of composites for airframes use hand lay-up, so other methods were not considered. It would be nearly impossible to succinctly consider the cost impacts of each type of composite, as they are incredibly numerous. Therefore, this research will focus on polymer matrix composites (particularly graphite and boron epoxy).

Since a sufficiently large database to test the significance of potential cost drivers or the cost impacts due to various combinations of these cost drivers does not exist, an alternate method was chosen. Historically, when analysts are faced with a scarcity of data, expert opinion has been the fallback position. In many cases (especially very early in a program's life, cost and schedule estimates are based almost entirely on the opinions of resident or contractor experts for labor hours, months of effort, and material requirements. There are a number of methods for eliciting expert opinion. For the purposes of answering the investigative questions contained in this thesis, a modified Delphi technique was selected.

The Delphi Technique

The Delphi technique can be described as a sophisticated method for developing a consensus of opinion among experts (4:145). Intuitively, a consensus among a group of experts is preferable to the opinion of one or even several experts. The concept of the Delphi technique originated as a spinoff of defense research in the 1940's. "Project Delphi" was an Air Force sponsored Rand Corporation study with the objective to obtain the best possible consensus of opinion among a group of experts (26:10).

Although closely related to common polling procedures, the Delphi technique offers a means to provide feedback of group data to the individual expert. The advantages in this methodology are in allowing the individual a chance to modify his opinion based on the collective views of the group and, secondly, retain the anonymity associated with a polling procedure (26:22). Additionally, by eliminating a face-to-face confrontation between the experts, the researcher avoids possible "groupthink" or the potential for dominance of opinion by any particular individual.

Although each of the many methods for eliciting expert opinion have distinct advantages, the Delphi technique has been shown to be effective for a variety of problem types. The most common use for the Delphi technique has been technological forecasting. However, a number of areas

exhibit the characteristics which tend to favor the use of Delphi. Some of the better reasons to use Delphi are:

1. The problem does not lend itself to precise analytical techniques, but can benefit from subjective judgement on a collective basis.
2. Time and cost make group meetings infeasible.
3. To assure validity, the "bandwagon" effect must be avoided.
4. There is a requirement for a broad range of diverse backgrounds with respect to experience and expertise. (26:4)

The Delphi technique is quite adaptable and fairly easy to use. However, like any methodology, there are also disadvantages to the Delphi.

The primary shortcomings to the Delphi technique include untested reliability, inadequate or unclear questions, problems in determining expertise, and unanticipated situations (8:6-10).

In order to avoid poor results, the designer must insure that each participant is fully aware of the time and resources required by the Delphi and interprets the evaluation scales in the same manner. Additionally, the monitor should avoid imposing views or preconceptions upon the participants. Finally, it is essential that disagreements be explored or there is a risk that participants will drop out, thus creating a faulty consensus (26:6). Although it is not possible to eliminate all of these potential problems, care should be taken to minimize the impact to the research.

There are two primary factors which determine the effectiveness of the Delphi. The first is the composition of the panel of experts. In order for the Delphi to provide useful results, the participating experts must be truly knowledgeable in the field from which the questions are drawn (6:140). Secondly, there must be a minimum number of participants in order to take advantage of the "Rule of Numbers."

Since the composition of the panel of experts is critical to the success of the Delphi technique, a list of potential participants was drawn from a wide variety of both industry and government sources. In general, Delphi results improve in a linear fashion as experts are added one-by-one until the group size reaches eleven, where reliability increases at a much lower rate (8:6-10). Therefore, approximately 25 individuals, considered to be experts in the field of composite cost estimating, were contacted.

Panel Selection

After the decision was made to use the Delphi technique, the first step was selecting the group of experts. Expertise in a field can involve a number criteria including education, professional training, experience, and depth of knowledge. Potential candidates for panel experts were: authors of published articles or models dealings with composites,

recommended by peers, or acknowledged in refereed literature as experts.

The current applications for composites among government prime contractors is extremely diverse. Most companies have experience with only a limited number of aircraft types. Manufacturing methods, automation levels, and production facilities vary a great deal among different companies. While individuals from a given company may be experts within their own company, it is important that panelists have a wide diversity of experience. Therefore, in order to avoid bias, candidates were chosen from a number of government contractors as well as from among government employees.

Experts from a particular company can offer valuable insights from their individual company's perspective, while government employees are more likely to have a more general knowledge. In this manner a consensus will have a greater likelihood of reflecting the current industry as a whole.

To ensure useful results, it is essential that panelist participation is sincere. Sincerity is achieved by explaining fully the requirements of the Delphi, the purpose of the questionnaire, and ascertaining the candidates willingness to participate. Telephone conversations with the 25 potential panelists garnered 15 who were willing to take part in the experiment. A letter of explanation (Appendix A) as well as the first round questionnaire was provided to each of the fifteen experts.

Questionnaire Development

There are no set rules for the format of Delphi questionnaires. Typically, a Delphi study would involve three rounds of questions. The initial questionnaire serves to provide the general focus for more specific questions in the following two rounds. There are two common ways in which to construct the initial questionnaire. The first method involves sending a vague description of the problem area to the participating experts in order to elicit their views on the specific areas for concentration (6:140). The other method is to base your initial questionnaire on a thorough review of the literature and then methodically sample the relevant areas (32:4).

For the purposes of this research, the initial questionnaire was eliminated. Rather, a review of the literature as well as phone conversations with non-participating experts were used to formulate specific questions. Since the overall problem of composite cost estimating is far too complex an area for a single exercise, the field of interest was narrowed to the point where specific questions could be determined without the need for an initial questionnaire.

The first round questionnaire (Appendix B) was constructed in such a way as to answer the investigative questions, while remaining within the scope of interest .

The questions were designed to minimize ambiguous or irrelevant answers. In general, the Delphi technique is used to forecast the future. For the purposes of this research, however, the intent was to estimate the present. This difference permitted the use of very specific questions which reduced the potential for ambiguity. In order to maintain clarity, assumptions were included at the top of each questionnaire.

Experts were asked to indicate their estimate of labor hours, broken down into labor categories, for various combinations of potential cost drivers. Each combination of variables was constructed in such a way as to provide as close to an exhaustive set of airframe scenarios as possible. Additionally, the assumptions were designed to narrow the range of focus to current conditions and elimate as much ambiguity as possible.

Unfortunately, a very poor response rate (only three responses were received by the due date) prompted further communication with the experts. Many of the experts felt that the purely quantitative nature of the original questionnaire: 1) required too much time to complete, 2) exceeded any one individual's range of expertise, and 3) was based on scenarios and labor category breakouts which would vary too greatly between contractor, subcontractor, and programs to be useful as a basis for research. Therefore, conversations with the experts as well as comments on first

round responses, resulted in a modification of the questionnaire and a new round 1 iteration.

For the modified round 1 questionnaire (Appendix C), experts were asked to indicate their responses to each measurement question in terms of the impact on 4 categories of labor hours using an ordinal scale. Therefore, for the 24 questions, 96 items were explored. The scale for the first iteration was subjective in nature with possible responses varying from far fewer hours to far more hours. The second iteration (Appendix D) associated specific ranges of values to the categories from iteration one. The measurement scale was designed to eliminate possible differences in interpretation the various contractors as well as to facilitate relevant responses from participants.

Because of the modified nature of this Delphi study, only two iterations were conducted. Each iteration was carried out via hand-delivery for government personnel and through facsimile transmission for contractor participants. This methodology permitted:

1. A wide variety of experts, separated by large distances, to participate with a minimum of inconvenience.
2. Rapid turn-around time.

In order to prevent bias, responses were not matched with specific participants when tabulating results (29:191).

Analysis

The primary method for analysis of Delphi results involves the use of central tendency characteristics as a measure of agreement among the experts. The median and the mode are measures of central tendency for ordinal scales, with the mode being the most useful for measuring consensus among experts (12:88-89). The mode is defined as the value that occurs most frequently in a set of observations (28:14).

Results for the first iteration were provided to the participants as a percentage of experts indicating a particular response for each question. Experts were asked to reconsider their original response based on the additional information. If an expert's second iteration response differed significantly from the majority response from the first round, the expert was asked to provide rationale (4:159). Typically, the majority of responses do not change between iterations, therefore results tend to converge toward the majority opinion (3:1).

Since experts' answers covered a range of responses, second iteration results for each of the 96 items were analyzed based on mode and interquartile ranges. Interquartile ranges divide response into four groups of equal size, with the median representing the 50th percentile (28:25-26). Consensus was determined when 70% or more answers constituted the mode. Therefore, for those questions where a consensus was reached, that result constituted the

group's estimate. For those questions not achieving consensus, the second round median was used to indicate the group's estimate. A further comparison of round one and two was conducted in an attempt to establish possible rationale for changes due to the subjective versus quantitative scales.

Chapter Summary

This chapter presented the methodology used to provide data necessary to answer the investigative questions. First, a general outline of the required data was provided, followed by a description of the Delphi process. Next, an overview of the questionnaire development and expert selection process were discussed. Finally, the chapter concluded with a description of the analysis process. Chapter four will discuss the analysis results and research findings.

IV. Analysis and Findings

Data Collection

Round One. The first Delphi round was telefaxed or hand delivered to 15 panelists on 19 June 1991. The experts were asked to respond not later than 26 June 1991. The first round was ended 28 June 1991 with 12 of the 15 questionnaires received. The remaining 3 experts were contacted to inquire as to the status of the questionnaire. Two of the experts contacted expressed a continuing desire to participate and stated that responses would be sent promptly. The third expert determined that his opinion would be based entirely on second hand data rather direct knowledge or experience and declined to participate. No further responses were received. Therefore, the first round was based on 12 questionnaires. Although 25 experts were originally solicited, expertise in composite cost estimating is limited. The findings represent the point expertise of this currently limited population. The name and organization for each expert is given in Table 1.

During analysis of round two responses, not all experts completed the entire questionnaire. In several instances, experts avoided answering questions where they felt their personal experience was inadequate to competently respond to the question. In one case, an expert felt that several of the variable combinations were infeasible and declined to

Table 1: Expert Panel

Respondent #	Expert Name	Organization Name
1	Capt. Hugh Bolton	ASD/FMCR
2	Paul Labar	General Dynamics Corporation
3	Fred Mungia	Lockheed Aeronautical Systems Company
4	Ed Peck	ASD/NASP
5	Paul F. Pirrung	WL/MTPN
6	Susan Resetar	Rand Corporation
7	Steve Schnaier	Grumman
8	Robert B. Schwenke	ASD/FMCR
9	Al Skewis	Boeing Aerospace
10	Mike Snead	ASD
11	Dr. F. S. Timson	Northrop Corporation
12	Ray Yarck	McDonnell Aircraft Co.

answer. Analysis revealed that no experts selected answers indicating a reduction in labor hours for any scenario due to the use of composite materials. Therefore, selections "A" and "B" were eliminated for the proceeding round. As previously discussed in Chapter III, the mode was used to determine group consensus. A consensus was established when 70% or more of the experts agreed upon the same response. Results for round one, as provided to the experts, are displayed in the second round questionnaire found in Appendix D.

Round Two. Once the results from round one were determined, the same questions were again sent to each expert, but with two differences. First, the ordinal scale from the first round was changed from subjective

delimitations to quantitative ranges to better establish the impact to labor hours in a useable manner. Secondly, the responses tc the first round were provided to the experts in terms of the percentage of total experts who indicated each particular answer. Additionally, any comments made in the previous round were included.

For round two, experts were encouraged to compare their initial responses to the group responses and change their answers if, on further consideration, they had revised their opinion. Further, the experts were informed that no changes needed to be made, but were asked to provide a short rationale if their response differed significantly from the norm.

The second round was telefaxed or hand delivered to the panelists on 1 July 1991. The response date for round two was originally 8 July 1991, but due to the holiday weekend, was extended an additional week. Round two was terminated on 15 July 1991, after 9 responses were received. The remaining three experts were contacted to ensure they had received the second round questionnaire and to ascertain their willingness to continue participation. One expert indicated that his round one responses should be used for round two. Another expert promptly returned the second round questionnaire, while the other response was never received. Second round responses are displayed in Appendix E.

Synopsis of Delphi Results

The two round Delphi survey resulted in a consensus in 67 of the 96 areas questioned. In general, this indicates that in about two-thirds of the cases the experts were in agreement as to the impact composite materials have on labor hours. Typically, the areas most likely to result in no consensus were the more complex scenarios where larger percentages of composites were involved. This is understandable since these are the areas where little actual experience exits.

For those questions where a consensus was not achieved, the median will be used to indicate the expert's opinion. In many cases, the responses came very close to meeting a consensus, therefore the median response still provides a fairly good indicator of majority expert opinion. The differences in interpreting the initial subjective responses from the first iteration (about the same, more, and far more) and translating those responses into actual labor hour impacts ranges used in the second iteration seems to account for large portion of opinion variation. Therefore, a comparison of round one and two responses should give valuable insight into the resulting range of answers. Table 2 summarizes the results of investigative questions 2-4, which are discussed in detail next.

Investigative Question #2

The second investigative question was to determine

Table 2: Investigative Questions 2-4 Summary

Change	Eng. Hrs.	Mfg. Hrs.	Tool Hrs.	QA Hrs.
Increase Composite Weight	C	D*	D*	D*
Increase Part Complexity	D*	D	D	D*
Increase Load-Bearing Role	D	D	D*	D*
Increase Hand Lay-Up	C*	E*	D*	D*
Increase Part Size	C*	D	D*	D*
Increase Low Observability	D*	D*	D*	D*

Legend

"C" denotes a 1.0 to 1.5 times increase in labor hours
"D" denotes a 1.5 to 2.0 times increase in labor hours
"E" denotes a 2.0 to 2.5 times increase in labor hours
"*" denotes a consensus repsonse

whether or not the relationship between cost (in labor hours) and weight holds true for composite airframes. The measurement question related to investigative question two is shown in Table 3.

Table 3: Investigative Question #2 Measurement

1. Increasing the weight of composites as a percentage of total unit weight.

   Engineering Hours: ____
   Manufacturing Hours: ____
   Tooling Hours: ____
   Quality Assurance Hours: ____

During the Delphi, consensus was obtained for Manufacturing, Tooling, and Quality Assurance hours. In all three cases, the experts agree that increases in composite weight as a percentage of total weight will result in 1.5 to 2.0 times

more labor hours than for an all metal airframe (see Appendix E, question #1).

Although no consensus was obtained for Engineering hours, the results, especially when compared to round one, are still quite useful. Six of eleven experts agreed that labor hours would be in a range of 1.0 to 1.5 times that for all metal, while four said that the range would be 1.5 to 2.0 times higher. On the other hand, round one resulted in a consensus view that it would require more hours than aluminum. This suggests that the implementation of a quantitative range for round two resulted in the divergence of opinion due to different interpretations of the first round scale. Since the median response in this case is 1.0 to 1.5, it seems plausible that the labor hour increase will be towards the top of the range.

The results from question one are consistent with current cost models discussed in chapter 2. In every reviewed parametric model which used composite weight as a cost driver. the coefficient indicated a larger increase in cost due to increases in composite weight than due to increases in metal weight as a percentage of the whole. It should be noted, however, that several experts cautioned the analyst to keep in mind that the typical composite structure may weigh considerably less than its equivalent in metal. This reduction in weight should be taken into account

whenever calculating the impact of an increasing percentage of composites in an airframe.

Investigative Questions #3 and #4

The third investigative question dealt with whether there were significant cost drivers, other than weight, which could account for the presence of composites. If such cost drivers are found, question four deals with whether the relationship is increasing or decreasing. The Delphi measurement questions dealing with investigative questions three and four are shown in Table 4.

During the Delphi, the experts failed to reach a consensus in only 5 of 20 areas for this investigative question. Comparison between rounds one and two shows a high degree of consistency between rounds (refer to Appendix E).

Survey Question 2. This question resulted in a consensus for both Engineering and Quality assurance hours. In both cases the experts agreed that an increase in composite shape complexity would result in 1.5 to 2.0 times more labor hours compared to metal. Although not sufficient to obtain a consensus, 7 of the eleven experts chose selection "D" for both Manufacturing and Tooling. Therefore, the median response of 1.5 to 2.0 appears to be a good indicator of the group opinion. Experts who did not agree with the median response, with one exception, chose the higher range.

Table 4: Investigative Question #3 & 4 Measurement

2. Increasing the complexity of composite shapes utilized in an airframe.

   Engineering Hours: ______
   Manufacturing Hours: ______
   Tooling Hours: ______
   Quality Assurance Hours: ______

3. Increasing the percentage of load-bearing composite parts.

   Engineering Hours: ______
   Manufacturing Hours: ______
   Tooling Hours: ______
   Quality Assurance Hours: ______

4. Increasing the percentage of composites requiring hand lay-up.

   Engineering Hours: ______
   Manufacturing Hours: ______
   Tooling Hours: ______
   Quality Assurance Hours: ______

5. Increasing the size of composite parts.

   Engineering Hours: ______
   Manufacturing Hours: ______
   Tooling Hours: ______
   Quality Assurance Hours: ______

6. Increasing the use of composites for purposes of low observability.

   Engineering Hours: ______
   Manufacturing Hours: ______
   Tooling Hours: ______
   Quality Assurance Hours: ______

The results for this question are consistent with information found during the literature review. Increased part complexity usually results in greater engineering efforts in ply lay-up drawings, planning proper fiber orientation, and increased modeling due to the variability in composite properties. Higher complexity parts also require more complex tooling and eliminate the use of several of the less labor intensive fabrication methods, thus increasing both tooling and manufacturing hours. Finally, increased part complexity also increases the likelihood of faults within the composite plies, delamination, or lack of bond integrity; thus requiring a great deal more time spent on quality assurance.

Part complexity appears to be a significant cost driver. As composite parts become more complex, associated labor hours increase. However, the relationship may or may not be a mathematical one. A potential problem in using complexity in parametric equations is quantifying the degree of complexity. In fact, of the models discussed, only one regression model had a variable for complexity and it dealt with the aircraft as a whole not with airframe parts. Therefore, the analyst must determine the best way in which to incorporate the impact into a cost model on an individual basis.

Survey Question 3. This question addresses the possible impact on labor hours due to increasing the percentage of

load bearing composites. A consensus of opinion was obtained in the Tooling and Quality Assurance areas. This is an improvement over round one where no consensus was obtained. For both areas, the consensus opinion was an increase of 1.5 to 2.0 times the hours for metal. The remaining areas, Engineering and Manufacturing, resulted in a fairly wide dispersion of answers whose median responses were also in the 1.5 to 2.0 range.

The diversity of opinion for this question is not unexpected. Although it is quite likely that material costs would increase as load bearing roles increase (requirement for higher quality material), the effect on labor hours is an area of dispute. However, the results are consistent with the rationale presented in chapter one. Load bearing parts tend to have primary roles which require tighter specification tolerances and incur far higher failure costs than secondary parts. Therefore, it is reasonable that such parts will require a corresponding increase in labor to produce.

The two labor categories which achieved a consensus are both areas where it is more likely that impacts on labor will be predictable. Primary (load bearing) structures must have more precise tooling and, because of their importance, will be subject to more quality assurance efforts. Thus, a consensus in these areas is not surprising.

Engineering and Manufacturing, on the other hand, are subject to conflicting views. One possible view is that no additional effort above that required for any composite will be necessary as long as the tooling is sufficiently precise and quality assurance suitably rigorous. However, the median response for both areas is compatible with opposing view that both Engineering and Manufacturing are subject to the same considerations as the other areas and will increase to the same degree.

Results indicate that the percentage of composites in a load bearing role is a significant cost driver. Labor hours can be expected to increase as more composites become load bearing. However, as for complexity, the relationship is not necessarily mathematical. Therefore, the usefulness of load bearing percentage in an actual model must be determined on a case by case basis. Nevertheless, the information should prove useful even if not incorporated directly into a model.

Survey Question 4. This question deals with the labor hour impact as a result of increasing hand lay-up. As might be expected, since this question deals with an area where a great deal of experience exists, a consensus was achieved in all four labor categories. The mode response for Engineering hours was 1.0 to 1.5. Manufacturing hours resulted in a mode response of 2.0 to 2.5. The mode response for both Tooling and Quality Assurance was 1.5 to 2.0. The results for this

question also improved from round one where only two areas achieved consensus.

Results for this question are completely consistent with the literature review as well as several of the models discussed. Hand lay-up is one of the more labor intensive fabrication techniques and would be expected to increase labor hours, especially in the Manufacturing cost element. In fact, one expert stated that the primary reason for the expense of composites is the lack of automation being used by the composite industry.

Like Manufacturing, increased hand lay-up can be expected to increase labor hour in Tooling and Quality Assurance. Since hand lay-up techniques are typically very slow and generally require autoclave curing, tools must often be duplicated to avoid curing lags. Additionally, repeated uses in high temperature autoclaves often necessitate re-tooling which drives up associated tooling hours. Finally, since hand lay-up is not nearly as precise as automated techniques, additional quality assurance must be performed to insure proper ply orientation and adequate lamination.

Although the consensus for Engineering hours may seem to contradict the results from the other areas, this is not the case. Once a part is designed and tested, and drawings complete; there is little difference in engineering regardless of fabrication technique. Therefore, simply increasing the amount of hand lay-up would not require any

additional engineering effort. Thus, while an increase in composites may result in higher engineering labor, differences in fabrication probably would not increase them any further.

The percentage of hand lay-up appears to be a significant driver of cost in the Manufacturing, Tooling, and Quality Assurance labor categories. A potentially useful way to incorporate this impact into a model is by indicating the type of fabrication technique used. As the use of automation increases, the relative differences in labor hours between manual and automated techniques will probably also increase. Therefore, the modeler should be aware of the particular fabrication techniques used and the extent of their use on any specific program in order to properly capture the resulting impact on cost.

Survey Question 5. This question deals with labor hour impacts as a result of increasing size. During the Delphi, consensus was obtained in the Engineering, Tooling, and Quality Assurance areas. The experts agreed that increasing the size of composite parts would result in a 1.0 to 1.5 times increase in engineering labor hours. The increases in labor hours for both Tooling and Quality Assurance were 1.5 to 2.0. The median response for Manufacturing was also in the 1.5 to 2.0 range. Only one area received a consensus in round one.

The engineering consensus is not surprising. There should be little if any impact on engineering activity as a result of simply increasing the size of the part. Both tooling and quality assurance, however, would become more difficult as well as time consuming as part size increases. Tools would have to be made larger, while still remaining within tolerances. As part size becomes very large, autoclaves must also be made larger to accommodate both parts and tools. Larger parts have a proportionately higher potential for error in ply alignment and delamination, which necessitates a corresponding increase in the time required to perform quality inspections. Therefore, results in all three areas are consistent with information found in a review of the literature.

The one labor category where a consensus was not obtained, manufacturing, received 7 of 11 responses which agreed with the median response. It is reasonable that size increases result in greater fabrication difficulty, especially when the process is manual. As size increases, the potential for error in laying-up the raw material also increases. Often, the raw material form is not particularly well suited for very large parts and must be placed end-to-end or side-by-side which adds the requirement for proper joining. Finally, some of the more labor efficient fabrication techniques are size limited and large parts must therefore be made using more labor intensive techniques.

Although part size can be considered a significant cost driver, it may be difficult to quantify. For example, when does a part become large enough to result in increased labor hours? In any event, the information provided should at least make the analyst aware that size can be a contributing factor to increased costs; especially when a program utilizes parts which are larger than the "norm" for the manufacturer.

Survey Question 6. This question deals with the impact of using composites for the purposes of low observability. This question obtained a consensus in all four labor categories. The consensus response for each category was a 1.5 to 2.0 times the increase in labor as compared to metal. The results for round two improved slightly from round one where three areas had a consensus response.

Several experts included comments to this question which indicate that low observability considerations will increase labor regardless of material used. When this effect is coupled with the already more complex composites, the effect is simply compounded. Stealth technology often requires special design considerations, complex shapes, toxic material usage, and very tight tolerances. Each of these requirements impact on labor hours. Therefore, it is not surprising that labor hours increase significantly in all categories.

The use of composites for reasons of low observability appears to be a significant cost driver in all categories. It is apparent that any stealth application will increase

costs. Some models have simply included a multiplier factor to account for the use of stealth technology. However, as in the use of the other cost drivers discussed in this chapter, the analyst must model the cost impacts for low observable composites in a manner best suited for each particular case.

Investigative Question #5

This question deals specifically with the effects of various combinations of cost drivers. Although there were six potential cost drivers explored in investigative questions one through four, only composite weight and complexity were used for investigative question five. Therefore, the Delphi questionnaire used in this study cannot account for combination effects from the other four variables.

Weight was chosen because it is the most readily quantifiable as well as most familiar cost driver. Composite part complexity was determined to be fairly quantifiable and readily generalized across aircraft types. The other potential cost drivers were considered either too airframe or aircraft type specific to be used for the purpose of answering this investigative question. Measurement questions were separated by aircraft type in order to provide more useful insight into how variable combinations impact specific classes of airframes. Measurement questions which deal with investigative question 5 for fighter aircraft can be seen in Table 5.

Table 5: Investigative Question #5 Measurement (Fighters)

7. A fighter aircraft with 50% or more composites and at least 50% of composites are complex in shape.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

10. A fighter aircraft with 50% or more composites and less than 50% of composites are complex in shape.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

13. A fighter aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

16. A fighter aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

19. A fighter aircraft with less than 25% composites and at least 50% of composites are complex in shape.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

22. A fighter aircraft with less than 25% composites and less than 50% of composites are complex in shape.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

Fighters. Of the three categories of aircraft, the most extensive experience base in composites falls within the fighter aircraft. Most composite databases are comprised almost entirely of fighters, while only a few have bombers or transport airframes. Therefore, of the three airframe categories, it can be expected that fighters will receive the greater number of consensus responses. Refer to Appendix E for expert response count.

Engineering Hours. A consensus was obtained in the Engineering category for 3 of 6 questions. Since engineering is an area of contention among experts, this result is not surprising. Some experts believe that composites will require additional effort in each stage of a program's life due to the increased complexity inherent in composites. Thiswould result in more time spent on analysis, test, and drawings. Other experts contend that while time spent early on will indeed be greater, later efforts will dwindle to the point that the overall engineering effort will not be changed. The final view is that the earlier increased effort will far outweigh the later reductions. Whatever the case, it is apparent from the results that opinion varies significantly, especially for the more complex scenarios.

The median response for question 7 is 1.5 to 2.0, where the majority of dissenters chose the higher range. Question 10 had a consensus response also in the 1.5 to 2.0 range. Question 13 received 7 of 11 responses in the median response

range of 1.5 to 2.0. A consensus of opinion was achieved on questions 16, 19, and 22 where experts agreed that labor hours would increase from 1.0 to 1.5 times that required for a metal airframe. The same number of consensus opinions was obtained in round one.

As stated previously, the more complex scenarios resulted in the widest disagreement. Consensus opinions were found in scenarios where the percentage of composites fell to the 25 to 50 percent range and below. Part complexity also contributed to the differences in opinion in the higher percentage composite scenarios.

Manufacturing Hours. A consensus was obtained in 3 of 6 questions. This labor category appeared to be very sensitive to changes in part complexity rather than percentage of composites. This outcome is understandable considering the groundrule of at least 80% hand lay-up. Part complexity would be expected to have a much greater impact on manual labor hours than would simple increases in composite percentage. Disagreement appears to have arisen based on the degree of the impact.

The median response for question 7 was 2.0 to 2.5, while a consensus of 1.5 to 2.0 was obtained in question 10. The only difference in these scenarios was in the percentage of complex parts. Thus, a reduction in complexity of the parts can be seen to reduce the required labor hours.

Question 13 obtained a consensus in the 1.5 to 2.0 range, while question 16 had a median response of 1.5 to 2.0 with all disagreement falling in the lower range. Clearly, the difference here is a result of a dispute as to how much a reduction in complexity would effect labor hours. A significant observation is the similarity in responses between questions 10 and 13. The same consensus range was obtained in both cases, one with a higher percentage of composites and the other with more complexity. This result appears to confirm the greater impact of complexity on manufacturing labor.

The median response for question 19 was the 1.0 to 1.5 range. A 100% consensus view of 1.0 to 1.5 was found for question 22. Again, the only difference in these scenarios was due to the percentage of part complexity. Question 19, with a higher percentage of complex parts, received four responses in the higher (1.5 to 2.0) range.

Tooling Hours. Four questions received a consensus in this category. The tooling category also seems more responsive to part complexity, though the relationship is not as clear as for manufacturing. The median response for question 7 was 1.5 to 2.0, while question 10 received a consensus in the same range. Again, the only difference in these two scenarios is the percentage of complex composite parts. Question 7 had 4 of 11 experts select the 2.0 to 2.5 range, six in the 1.5 to 2.0 range and only one in the lower

range. This spread of responses, especially in light of the consensus in question 10, suggests that experts are not sure as to the magnitude of the impact increased part complexity will have on high percentage composite airframes.

Similarly, question 13 received a consensus in the 1.5 to 2.0 range and a median response in the same range for question 16. The results for medium percentage composite airframes are opposite those for high percentage composites. Question 16 received 4 of 11 responses in the lowest impact range and 7 of 11 in the median range. A reduction in part complexity appears to once again cause the difference of opinion.

Finally, both questions 19 and 22 achieved a consensus in the 1.0 to 1.5 range. Question 19 received only 2 of 11 responses indicating the higher range, while 100% agreed in question 22. It seems clear that part complexity does not carry the same impact in the low percentage composite airframes as it does when the percentage is higher.

Quality Assurance Hours. Five of six questions received a consensus in this area. The only question which did not achieve consensus is question 7, the most complex scenario. There is no apparent trend here in regards to either total percentage or part complexity. A combination of the two variables appears to be the primary response driver. However, for equal percentage composite scenarios, complexity again appears to have a definite impact.

Question 7 was widely dispersed, with the 1.5 to 2.0 median range receiving 6 of 11 votes. Dissenters were fairly evenly spread over the remaining ranges. Question 10 achieved consensus in the 1.5 to 2.0 range, where apparently all of the higher range dissenters from question 7 moved their response to the middle range due to the reduction in complex composite parts.

Questions 13, 16, 19, and 22 had consensus responses. The consensus for question 13 was 1.5 to 2.0, while it was 1.0 to 1.5 for the remaining questions. Again, question 22 had a unanimous response. Dissenters, for each of the higher percentage scenarios, chose the higher impact range. This supports the conclusion that, while the combination of composite complexity and total composite percentage effect the overall impact on labor, complexity is the driver when total percentage remains constant.

Bombers. As stated previously, very little experience exists in the use of composites on bombers. Although both the B-1B and B-2 utilize composites, these are the only bombers produced in the United States in the last 25 years. Additionally, the use of composites on the B-1B is somewhat limited and so few B-2's have been produced that little data is available. As a result, one expert declined to respond to bomber related questions. Measurement questions which deal with bomber aircraft for Investigative Question 5 can be seen in Table 6.

Table 6: Investigative Question #5 Measurement (Bombers)

8. A bomber aircraft with 50% or more composites and at least 50% of composites are complex in shape.

    Engineering Hours: ____
    Manufacturing Hours: ____
    Tooling Hours: ____
    Quality Assurance Hours: ____

11. A bomber aircraft with 50% or more composites and less than 50% of composites are complex in shape.

    Engineering Hours: ____
    Manufacturing Hours: ____
    Tooling Hours: ____
    Quality Assurance Hours: ____

14. A bomber aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

    Engineering Hours: ____
    Manufacturing Hours: ____
    Tooling Hours: ____
    Quality Assurance Hours: ____

17. A bomber aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

    Engineering Hours: ____
    Manufacturing Hours: ____
    Tooling Hours: ____
    Quality Assurance Hours: ____

20. A bomber aircraft with less than 25% composites and at least 50% of composites are complex in shape.

    Engineering Hours: ____
    Manufacturing Hours: ____
    Tooling Hours: ____
    Quality Assurance Hours: ____

23. A bomber aircraft with less than 25% composites and less than 50% of composites are complex in shape.

    Engineering Hours: ____
    Manufacturing Hours: ____
    Tooling Hours: ____
    Quality Assurance Hours: ____

Engineering Hours. Three of six questions received a consensus response. Questions 8, 11, and 14 had median responses of 1.5 to 2.0. However, question 8 also had a median response of 2.0 to 2.5 (since an even number of experts answered this question, it is possible to have a tie). Due to the nature of the answers, it is impossible to divide a category by two. However, the distribution of the answers would seem to indicate that the median response would probably be about 2.0.

Questions 17, 20, and 23 had consensus responses of 1.0 to 1.5. The consensus was unanimous for both questions 20 and 23. It is apparent that reductions in complexity and percentage of composites resulted in a much higher level of agreement among the experts. This is consistent with the degree of experience available in composite bombers. Both bombers produced in the United States would fall in one of the three categories where consensus was obtained.

Manufacturing Hours. Four of the six questions had a consensus response for this labor category. This is somewhat surprising since bombers are more likely to have large sized components and manufacturing was the only category not receiving a consensus on question 5.

Question 8 had a consensus response of 2.0 to 2.5, with the remaining responses fairly evenly distributed. Question 11 also had a consensus response, but in the 1.5 to 2.0 range. The only difference between these two scenarios is

the percentage of complex composite parts, indicating that the relationship between manufacturing labor and complexity will hold true for bombers as well as fighters.

Question 14 received a consensus in the 1.5 to 2.0 range, while question 17 had a median response of 1.0 to 1.5. Again, the only difference is the higher percentage of complex parts which supports the assertion stated above.

The median response for question 20 was 1.0 to 1.5, while 23 had a unanimous consensus of 1.0 to 1.5. These results further support the relationship between manufacturing labor hours and composite part complexity. Questions 17 and 20 received identical distributions of responses, while 23 was unanimous. Therefore, while the median responses were the same as the consensus, those experts not in agreement felt a greater impact should be expected due to complexity.

<u>Tooling Hours</u>. This category also achieved consensus in four of the six questions. While there were differences in which questions had a consensus response, the group estimate for each question was identical to the ones in Manufacturing. Thus, any conclusions based on the patterns observed in the Manufacturing category must necessarily also follow in this labor category.

Question 8 had a median response of 2.0 to 2.5, while question 11 achieved consensus in the 1.5 to 2.0 range. The consensus for question 14 was 1.5 to 2.0 and question 17 had

a median estimate of 1.0 to 1.5. Similarly, questions 20 and 23 both had consensus estimates of 1.0 to 1.5.

<u>Quality Assurance</u>. The results for this labor category were similar to the previous two categories, where four of six questions achieved a consensus. Like the estimates for Manufacturing and Tooling; estimates for Quality assurance, although differing in questions having a consensus, were identical to those obtained in Engineering.

Question 8 had two median response ranges of 1.5 to 2.0 and 2.0 to 2.5, resulting in a probable response of 2.0. Question 11 received a consensus vote of 1.5 to 2.0. The median response for question 14 was 1.5 to 2.0, while questions 17, 20, and 23 each had a consensus in the 1.0 to 1.5 range.

<u>Cargo and Tanker Aircraft</u>. Like bombers, there is very little actual experience in the production of cargo or tanker aircraft using composites. The experience that does exist is limited primarily to modifications (tail sections, stabilizers, cargo doors, etc.) and to the C-17. Additionally, although the C-17 contains a fairly large amount of composites, the percentage of total weight as well as the percentage of complex parts is still quite small compared to the newer generation of fighters.

Again, as in the bomber category, only 10 experts chose to respond to cargo/transport related questions. Nonetheless, 19 of 24 labor categories in the six

cargo/tanker related questions achieved consensus. Measurement questions dealing with cargo/tanker aircraft for investigative question 5 can be seen in Table 7.

Engineering Hours. Four of six questions received consensus responses. Both non-consensus responses were in the high percentage composite scenarios. This is not surprising, since virtually no experience in this area exists. Questions 9 and 12 both had median estimates of 1.5 to 2.0. The consensus answer for questions 15, 18, 21, and 24 was the range of 1.0 to 1.5.

Manufacturing Hours. Five of six questions had a consensus estimate for this labor category. Unlike the results for engineering where no pattern is visible, manufacturing appears to follow the more familiar pattern in relation to part complexity. The median response for question 9 was 2.0 to 2.5, while questions 12 and 15 had consensus estimates in the 1.5 to 2.0 range. The remaining questions, 18, 21, and 24, had consensus estimates of 1.0 to 1.5. As previously indicated, the estimates appear to be more responsive to changes in composite part complexity than to changes in percentage of composites for this labor category.

Tooling. This labor category also achieved consensus in five of six questions. Question 9 had a median response of 1.5 to 2.0, while questions 12 and 15 had a consensus in the same range. Questions 18, 21, and 24 each

Table 7: Investigative Question #5 Measurement (Cargo/Tanker)

9. A cargo or tanker aircraft with 50% or more composites and at least 50% of composites are complex in shape.

   Engineering Hours: _____
   Manufacturing Hours: _____
   Tooling Hours: _____
   Quality Assurance Hours: _____

12. A cargo or tanker aircraft with 50% or more composites and less than 50% of composites are complex in shape.

   Engineering Hours: _____
   Manufacturing Hours: _____
   Tooling Hours: _____
   Quality Assurance Hours: _____

15. A cargo or tanker aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

   Engineering Hours: _____
   Manufacturing Hours: _____
   Tooling Hours: _____
   Quality Assurance Hours: _____

18. A cargo or tanker aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

   Engineering Hours: _____
   Manufacturing Hours: _____
   Tooling Hours: _____
   Quality Assurance Hours: _____

21. A cargo or tanker aircraft with less than 25% composites and at least 50% of composites are complex in shape.

   Engineering Hours: _____
   Manufacturing Hours: _____
   Tooling Hours: _____
   Quality Assurance Hours: _____

24. A cargo or tanker aircraft with less than 25% composites and less than 50% of composites are complex in shape.

   Engineering Hours: _____
   Manufacturing Hours: _____
   Tooling Hours: _____
   Quality Assurance Hours: _____

had a consensus estimate of 1.0 to 1.5. It is unclear whether the estimates varied due to impacts resulting from percentage composites or part complexity.

Quality Assurance. Once again, results in this labor category closely mirror those found in the engineering category. Question 9 had a median response and question 12 and 15 a consensus in the 1.5 to 2.0 range. Questions 18, 21, and 24 each achieved a consensus of 1.0 to 1.5. No pattern, except a reduction of hours due to decreases in percentage of composites, was apparent.

Investigative Question #6

This question deals with the impact of variable combinations from Investigative Question #5 and their impact across aircraft types. A summary of the results for each labor category by aircraft type can be seen in Table 8. Impact estimates for Table 8 are a combination of both median and consensus responses. For a differentiation between consensus and median estimates for particular questions, please refer to to Appendix E.

Engineering. Although differences in estimates do exist, there is apparently no pattern to to the differences across aircraft types. Cargo/Tanker and fighter labor hour impact estimates are lower than bombers in the scenario with large percentage of composites of high complexity. When 25 to 50% of the airframe is composite and at least 50% of the

composites are of complex shape, Cargo/Tanker aircraft had a lower impact estimate than fighters or bombers. Estimates for the remaining scenarios were identical across aircraft type.

Manufacturing. Estimates in this labor category were identical, but for one scenario. In the 25 to 50% composite

Table 8: Labor Hour Impact by Aircraft Type

SCENARIO	LABOR CATEGORY/AIRCRAFT TYPE											
	ENGINEERING			MFG			TOOLING			QA		
	F	B	C/T	F	B	C/T	F	B	C/T	F	B	C/T
50% OR MORE COMPOSITES AND AT LEAST 50% OF COMPOSITES ARE COMPLEX IN SHAPE	D	D/E	D	E	E	E	D	E	D	D	D/E	D
50% OR MORE COMPOSITES AND LESS THAN 50% OF COMPOSITES ARE COMPLEX IN SHAPE	D	D	D	D	D	D	D	D	D	D	D	D
25 TO 50% COMPOSITES AND AT LEAST 50% OF COMPOSITES ARE COMPLEX IN SHAPE	D	D	C	D	D	D	D	D	D	D	D	C
25 TO 50% COMPOSITES AND LESS THAN 50% OF COMPOSITES ARE COMPLEX IN SHAPE	C	C	C	D	C	C	D	C	C	C	C	C
LESS THAN 25% COMPOSITES AND AT LEAST 50% OF COMPOSITES ARE COMPLEX IN SHAPE	C	C	C	C	C	C	C	C	C	C	C	C
LESS THAN 25% COMPOSITES AND LESS THAN 50% OF COMPOSITES ARE COMPLEX IN SHAPE	C	C	C	C	C	C	C	C	C	C	C	C

AIRCRAFT TYPE
"F"=Fighter
"B"=Bomber
"C/T"=Cargo/Tanker

IMPACT LEGEND
"C"=1.0 to 1.5 times more hours
"D"=1.5 to 2.0 times more hours
"E"=2.0 to 2.5 times more hours

scenario where less than 50% of composites are complex in shape, the fighter aircraft estimate was higher than both bombers and cargo/tanker aircraft.

Tooling. The bomber aircraft impact estimate exceeded both fighters and cargo/tanker for the high percentage, high complexity scenario. Like the manufacturing category, fighters were estimated as having a higher labor hour impact than bombers or cargo/tanker aircraft in the 25 to 50% composite, low complexity scenario. All other scenarios resulted in identical estimates across aircraft types.

Quality Assurance. The results for this labor category are the same as those for engineering. The bomber aircraft impact estimate is higher than for either fighters or cargo/tanker aircraft in the high percentage, high complexity scenario. On the other hand, fighters and bombers are identical, while cargo/tankers have a lower estimate in the 25 to 50%, low complexity scenario.

Summary

This chapter presents the analysis and findings of the Delphi survey. Results from the data collection of both Delphi rounds are presented and summarized. Additionally, measurement questions for investigative questions two through six are presented and analyzed. Findings for each measurement question are presented in both narrative and tabular form. In the next and final chapter, research

conclusions as well as recommendations for further research will be discussed.

V. Conclusions and Recommendations

Overview

This chapter proposes conclusions based on the literature review as well as results obtained through the Delphi process. The intent of this research is to provide a guide for constructing composite cost models. Conclusions found in this chapter address each investigative question in turn. The conclusions should also provide analysts with a roadmap to the more detailed areas of interest within the guide itself. Additionally, this chapter will present recommendations for further research in the area of composite cost modeling.

Conclusions

Investigative Question #1. There are a number of cost models available to analysts which attempt account for impacts due to the use of composites. Each model has drawbacks as well as advantages. No single model is useful in every situation. The analyst is encouraged to compare results from several of the models, combine the models, or simply use information or techniques from the models to devise a methodology specific for a given application. Further, some of the models discussed are aircraft type specific, these should not be used outside their appropriate database.

Investigative Question #2. The relationship between weight and cost appears to hold true for composites as it does for metal. The relationship is increasing, so as composite weight increases as a percentage of total weight, labor hours will also increase. Labor hour increases in the engineering labor category can be expected to be 1.0 to 1.5 times greater than for metal. Increase in the percentage total weight of composites can be expected to have a 1.5 to 2.0 times greater impact than increases in metal weight.

Investigative Questions #3 and #4. Each of the proposed potential cost drivers appears to have a significant impact on labor hours. Increased composite part complexity can be expected to increase labor hours from 1.5 to 2.0 times more than similar increases in metal parts. Similarly, increasing the load bearing percentage of composites can be expected to result in a 1.5 to 2.0 times increase in labor hours. A 1.0 to 1.5 times increase in engineering hours can be anticipated if the requirement for hand lay-up is increased, while the impact on manufacturing should be a 2.0 to 2.5 times increase. Both tooling and quality assurance hours appear to increase from 1.5 to 2.0 due to increases in hand lay-up. Composite part size increases appear to result in a 1.0 to 1.5 times increase in engineering hours, while a 1.5 to 2.0 times increase can be expected in the remaining labor categories. Finally, a 1.5 to 2.0 times increase in labor

hours for each category can be anticipated due to the use of composites in a low observable role.

Investigative Question #5. A definitive relationship between cost in hours and combinations of composite weight (as a percentage of total weight) and composite part complexity cannot be established with any certainty. However, patterns in the labor hour impacts as a result of the changing scenarios suggest that labor hours are more responsive to one independent variable than the other in certain situations. The weight of composites as a percentage of total weight appears to be the predominant cost driver in the engineering category. However, when composite weight is between 25 and 50 percent, part complexity becomes increasingly important. Complexity appears to be the predominant cost driver for manufacturing hours, especially when a large percentage of the airframe is comprised of composites. Like manufacturing, tooling hours appear to respond most noticeably to changes in part complexity. The quality assurance category, like engineering, appears to be most effected by total percentage of composites. Again, however, in the 25 to 50 percent composite range a reduction in complexity can be expected to cause a reduction in labor hours.

Investigative Question #6. There is no discernable pattern to the labor hour differences among aircraft types. In only three scenarios were there any labor differences

across aircraft types. Bombers seem to require more engineering, tooling and quality assurance hours in high percentage, high complexity scenarios than do fighter or cargo/tanker aircraft. On the other hand, fighters appear to require relatively more manufacturing and tooling hours in the 25 to 50 percent composite range when complexity is relatively low. Finally, Cargo/tanker aircraft have a lower engineering and quality assurance labor requirement in the 25 to 50 percent composite, high complexity scenario than do bombers or fighters.

Recommendations

Recommendation #1. The Delphi appears to be a useful tool for this type of research. At a parts level, exploration into complexity, size, fabrication techniques, and other possible cost drivers should be possible with a subcontractor oriented Delphi approach. Although not particularly suited for use early in a program, part level information can be valuable later in the program or simply as an information base for composite cost relationships.

Recommendation #2. Although each of the potential cost drivers studied in this thesis appear to be significant drivers of composite labor hours, a more thorough study would be useful. It is unclear, at this point, if the variables are independent of each other. For example, is size a driver in and of itself, or only because it tends to result in a

higher total percentage of composites as one expert suggested? Additionally, potential cost drivers such as matrix/reinforcement material type or fabrication technique should be explored. Fabrication techniques, especially, will become increasingly important as automation becomes more prevalent. In fact, several experts suggested that composite parts produced by a totally automated system will be less expensive pound-for-pound that aluminum.

Recommendation #3. The use of scenarios with various combinations of total percent composites and composite complexity suggested some useful relationships. A study which further breaks down the scenarios into smaller classes (e.g. 10-20%, 20-30%, 30-40%, etc.) would provide additional visibility into the cost driver relationships. Further, such a study could lend support to conclusions drawn in this research, or find completely different patterns that were not visible in the limited number of scenarios provided here. Finally, different variable combinations offer additional avenues of research.

Recommendation #4. A study similar to the initial attempt made for this research still has potential. A Delphi survey of industry experts that solicits actual labor hour estimates for specific, but generic airframes could provide a great deal of valuable information. Such a study, however, should be based on very detailed scenarios. One possible avenue would be to provide experts with the labor hours

associated with actual all-aluminum airframes (F100, F-101, F-4, etc.) and ask them to provide labor hour estimates for producing the same airframe, but with varying percentages of composites.

Summary

This chapter presented the conclusions based on the literature review and Delphi process results. The chapter began by addressing the original research objective. Conclusions were presented as they related to the investigative questions. Finally, recommendations for further research to expand the body of knowledge addressed in this research were presented.

Appendix A: Initial Request Letter

7 May 1991

Dear Participant:

First, I would like to thank you for agreeing to participate. Without your assistance, gathering sufficient data to successfully complete my thesis may well have been impossible. Although there is not a lot that I can do to express my appreciation, you will be acknowledged in my thesis and you may have a copy of the finished product if you so desire.

As you may already know, the Delphi Method is a technique used to elicit the opinions of a group of experts in a manner which will produce a convergence of those opinions. I selected the Delphi Method as a tool to tap the widest possible spectrum of knowledge in the most efficient manner available. Therefore, even if you yourself cannot complete the entire worksheet, please feel free to have colleagues participate. Please include the full names and positions, including yourself, of all participants.

Some additional comments about the worksheet. Even if you do not consider yourself an "expert," your experience and those of any coworkers may offer valuable insights and perspectives which other "experts" may not possess. Therefore, please complete the worksheet as fully as possible. Remember, the scenarios represent completely generic aircraft. If you have actual data which can help you to fill in the worksheet or you have a model which you use to estimate hours for airframes, please use them. The manner in which the worksheet is completed is solely at the discretion of the expert. Also, please remember that in no way will individual experts be associated with specific estimates.

Finally, if for any reason you feel unable to complete portions of the worksheet simply put in a brief explanation instead of an estimate. This also applies to any scenario you feel is infeasible for a technical or other reason. If you wish to make any comments about your estimates, please do so at the bottom of the worksheet.

I am currently planning on two rounds (iterations) to encourage possible convergence. Please return the first iteration of the worksheet to me at the Fax number on the cover sheet NLT 20 May 1991. I will send the results of the first round back to you on 22 May.

If you have any questions, please feel free to call me at (513) 233-6882. Once again, I thank you for your participation.

Sincerely,

[Signed]

Capt. Jeffrey L. Isom
AFIT/LSG

Appendix B: Original Delphi Worksheet

BASIC ASSUMPTIONS:

1) ONLY RECURRING COSTS SHOULD BE ESTIMATED.

2) COSTS WILL BE EXPRESSED IN THOUSANDS OF HOURS.

3) ALL ESTIMATES WILL BE BASED ON THE CUMULATIVE AVERAGE HOURS OF 100 PRODUCTIONS UNITS.

4) ALL HOURS WILL BE BASED ON CARBON AND BORON POLYMER MATRIX COMPOSITES.

5) ASSUME A MINIMUM OF 80% HAND LAY-UP FOR COMPOSITES.

6) ASSUME NORMAL REWORK AND SCRAP RATES.

7) HOURS SHOULD INCLUDE EFFORT UP TO AIRFRAME ASSEMBLY. ADDITIONAL EFFORT FOR FINAL ASSEMBLY, CHECKOUT, OR SUBSYSTEM INSTALLATION SHOULD NOT BE INCLUDED.

8) ASSUME AN AVERAGE MIX OF MANUAL AND SEMI-AUTOMATED PRODUCTION FACILITIES.

9) ASSUME CURRENT TECHNOLOGY.

10) X1 = POUNDS OF AIRFRAME UNIT WEIGHT

11) X2 = PERCENTAGE OF COMPOSITES

12) X3 = PERCENT OF COMPOSITES FORMED INTO COMPLEX SHAPES.

13) H = HIGH VALUES (X1 > 75,000 LBS., X2 > 50%, X3 > 50%)

14) M = MEDIUM VALUES (25,000 LBS. < X1 < 50,000 LBS, 25% < X2 < 50%, 25% < X3 < 50%)

15) L = LOW VALUES (X1 < 25,000 LBS., X2 < 25%, X3 < 25%)

(E.G. THE C-17 WOULD BE CLASSIFIED AS FOLLOWS: X1 = H, X2 = L, X3 = M FOR HIGH AIRFRAME UNIT WEIGHT, LOW COMPOSITE PERCENTAGE, AND MEDIUM COMPLEX COMPOSITE SHAPE PERCENTAGE)

SCENARIO	X1	X2	X3	ENGINEER HOURS	TOOLING HOURS	ASSEMBLY HOURS	MFG HOURS	QA HOURS
1	H	H	H					
2	H	H	M					
3	H	H	L					
4	H	M	H					
5	H	M	M					
6	H	M	L					
7	H	L	H					
8	H	L	M					
9	H	L	L					
10	M	H	H					
11	M	H	M					
12	M	H	L					
13	M	M	H					
14	M	M	M					
15	M	M	L					
16	M	L	H					
17	M	L	M					
18	M	L	L					
19	L	H	H					
20	L	H	M					
21	L	H	L					
22	L	M	H					
23	L	M	M					
24	L	M	L					
25	L	L	H					
26	L	L	M					
27	L	L	L					

(ALL HOURS IN THOUSANDS)

Appendix C: First Round Questionnaire

For the questions below, assume the baseline aircraft is all metal. Indicate the effects to labor hours in each of the categories as a result of the following changes.

A	B	C	D	E
Far Fewer Hours	Fewer Hours	About the Same	More Hours	Far More Hours

1. Increasing the weight of composites as a percentage of total unit weight.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

2. Increasing the complexity of composite shapes utilized in an airframe.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

3. Increasing the percentage of load-bearing composite parts.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

4. Increasing the percentage of composites requiring hand lay-up.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

5. Increasing the size of composite parts.

    Engineering Hours: _____
    Manufacturing Hours: _____
    Tooling Hours: _____
    Quality Assurance Hours: _____

6. Increasing the use of composites for purposes of low observability.

Engineering Hours:	____
Manufacturing Hours:	____
Tooling Hours:	____
Quality Assurance Hours:	____

For the questions below, assume:

- composites are carbon polymer matrix
- minimum of 80% hand lay-up
- normal rework and scrap rates
- current technology
- average mix of manual and semi-automated labor

Indicate the changes in labor hours which would result in building the following aircraft as opposed to ones made entirely of metal.

A	B	C	D	E
Far Fewer Hours	Fewer Hours	About the Same	More Hours	Far More Hours

7. A fighter aircraft with 50% or more composites and at least 50% of composites are complex in shape.

Engineering Hours:	____
Manufacturing Hours:	____
Tooling Hours:	____
Quality Assurance Hours:	____

8. A bomber aircraft with 50% or more composites and at least 50% of composites are complex in shape.

Engineering Hours:	____
Manufacturing Hours:	____
Tooling Hours:	____
Quality Assurance Hours:	____

9. A cargo or tanker aircraft with 50% or more composites and at least 50% of composites are complex in shape.

Engineering Hours:	____
Manufacturing Hours:	____
Tooling Hours:	____
Quality Assurance Hours:	____

10. A fighter aircraft with 50% or more composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

11. A bomber aircraft with 50% or more composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

12. A cargo or tanker aircraft with 50% or more composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

13. A fighter aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

14. A bomber aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

15. A cargo or tanker aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

16. A fighter aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

17. A bomber aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

18. A cargo or tanker aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

19. A fighter aircraft with less than 25% composites and at least 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

20. A bomber aircraft with less than 25% composites and at least 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

21. A cargo or tanker aircraft with less than 25% composites and at least 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

22. A fighter aircraft with less than 25% composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

23. A bomber aircraft with less than 25% composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

24. A cargo or tanker aircraft with less than 25% composites and less than 50% of composites are complex in shape.

Engineering Hours: _____
Manufacturing Hours: _____
Tooling Hours: _____
Quality Assurance Hours: _____

Appendix D: Second Round Questionnaire

For the questions below, assume the baseline aircraft is all metal. Indicate the effects to labor hours in each of the categories as a result of the following changes.

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

1. Increasing the weight of composites as a percentage of total unit weight.

		C	D	E
Engineering Hours:	______	25%	58%	17%
Manufacturing Hours:	______		100%	
Tooling Hours:	______		92%	8%
Quality Assurance Hours:	______		83%	17%

2. Increasing the complexity of composite shapes utilized in an airframe.

		C	D	E
Engineering Hours:	______	8%	83%	9%
Manufacturing Hours:	______		58%	42%
Tooling Hours:	______		42%	58%
Quality Assurance Hours:	______		92%	8%

3. Increasing the percentage of load-bearing composite parts.

		C	D	E
Engineering Hours:	______	20%	40%	40%
Manufacturing Hours:	______	30%	50%	20%
Tooling Hours:	______	30%	50%	20%
Quality Assurance Hours:	______	30%	30%	40%

4. Increasing the percentage of composites requiring hand lay-up.

		C	D	E
Engineering Hours:	______	75%	25%	
Manufacturing Hours:	______		33%	67%
Tooling Hours:	______	33%	50%	17%
Quality Assurance Hours:	______	17%	75%	8%

5. Increasing the size of composite parts.

		C	D	E
Engineering Hours:	______	75%	25%	
Manufacturing Hours:	______	33%	67%	
Tooling Hours:	______	33%	67%	
Quality Assurance Hours:	______	42%	50%	8%

6. Increasing the use of composites for purposes of low observability.

		C	D	E
Engineering Hours:	____	9%	73%	18%
Manufacturing Hours:	____		82%	18%
Tooling Hours:	____	9%	73%	18%
Quality Assurance Hours:	____	9%	55%	36%

For the questions below, assume:

- composites are carbon polymer matrix
- minimum of 80% hand lay-up
- normal rework and scrap rates
- current technology
- average mix of manual and semi-automated labor

Indicate the changes in labor hours which would result in building the following aircraft as opposed to ones made entirely of metal.

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

7. A fighter aircraft with 50% or more composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	9%	45%	46%
Manufacturing Hours:	____		27%	73%
Tooling Hours:	____		36%	64%
Quality Assurance Hours:	____		36%	64%

8. A bomber aircraft with 50% or more composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	11%	44%	45%
Manufacturing Hours:	____		22%	78%
Tooling Hours:	____		22%	78%
Quality Assurance Hours:	____		22%	78%

9. A cargo or tanker aircraft with 50% or more composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	11%	44%	45%
Manufacturing Hours:	____		33%	67%
Tooling Hours:	____		33%	67%
Quality Assurance Hours:	____		33%	67%

10. A fighter aircraft with 50% or more composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	20%	70%	10%
Manufacturing Hours:	____		82%	18%
Tooling Hours:	____		82%	18%
Quality Assurance Hours:	____	27%	46%	27%

11. A bomber aircraft with 50% or more composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	22%	56%	22%
Manufacturing Hours:	____		78%	22%
Tooling Hours:	____		78%	22%
Quality Assurance Hours:	____	33%	34%	33%

12. A cargo or tanker aircraft with 50% or more composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	25%	75%	
Manufacturing Hours:	____		100%	
Tooling Hours:	____		100%	
Quality Assurance Hours:	____	25%	63%	12%

13. A fighter aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	37%	63%	
Manufacturing Hours:	____		89%	11%
Tooling Hours:	____		78%	22%
Quality Assurance Hours:	____	37%	52%	11%

14. A bomber aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	50%	50%	
Manufacturing Hours:	____		100%	
Tooling Hours:	____		88%	12%
Quality Assurance Hours:	____	50%	38%	12%

15. A cargo or tanker aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	62%	38%	
Manufacturing Hours:	____	12%	88%	
Tooling Hours:	____	12%	76%	12%
Quality Assurance Hours:	____	63%	25%	12%

16. A fighter aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	_____	60%	40%	
Manufacturing Hours:	_____	10%	90%	
Tooling Hours:	_____	10%	90%	
Quality Assurance Hours:	_____	50%	40%	10%

17. A bomber aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	_____	63%	37%	
Manufacturing Hours:	_____	12%	88%	
Tooling Hours:	_____	12%	88%	
Quality Assurance Hours:	_____	63%	25%	12%

18. A cargo or tanker aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	_____	75%	25%	
Manufacturing Hours:	_____	25%	75%	
Tooling Hours:	_____	12%	88%	
Quality Assurance Hours:	_____	63%	25%	12%

19. A fighter aircraft with less than 25% composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	_____	73%	18%	9%
Manufacturing Hours:	_____	30%	60%	10%
Tooling Hours:	_____	45%	46%	9%
Quality Assurance Hours:	_____	55%	36%	9%

20. A bomber aircraft with less than 25% composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	_____	78%	11%	11%
Manufacturing Hours:	_____	22%	67%	11%
Tooling Hours:	_____	45%	46%	11%
Quality Assurance Hours:	_____	56%	33%	11%

21. A cargo or tanker aircraft with less than 25% composites and at least 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	_____	78%	11%	11%
Manufacturing Hours:	_____	45%	46%	11%
Tooling Hours:	_____	56%	33%	11%
Quality Assurance Hours:	_____	56%	33%	11%

22. A fighter aircraft with less than 25% composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	82%	18%	
Manufacturing Hours:	____	64%	36%	
Tooling Hours:	____	73%	27%	
Quality Assurance Hours:	____	64%	36%	

23. A bomber aircraft with less than 25% composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	89%	11%	
Manufacturing Hours:	____	67%	33%	
Tooling Hours:	____	78%	22%	
Quality Assurance Hours:	____	67%	33%	

24. A cargo or tanker aircraft with less than 25% composites and less than 50% of composites are complex in shape.

		C	D	E
Engineering Hours:	____	89%	11%	
Manufacturing Hours:	____	67%	33%	
Tooling Hours:	____	78%	22%	
Quality Assurance Hours:	____	67%	33%	

NOTE: If possible, please provide a short explanation if your answer differs significantly from the norm. This will increase the usefulness of my research tremendously. Thank you

Appendix E: Second Round Responses

For the questions below, results shown are the number of experts who selected each response.

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

1. Increasing the weight of composites as a percentage of total unit weight.

	C	D	E
Engineering Hours:	6	4	1
Manufacturing Hours:	2	8	1
Tooling Hours:	2	8	1
Quality Assurance Hours:	1	10	

2. Increasing the complexity of composite shapes utilized in an airframe.

	C	D	E
Engineering Hours:	2	9	
Manufacturing Hours:	1	7	3
Tooling Hours:		7	4
Quality Assurance Hours:		11	

3. Increasing the percentage of load-bearing composite parts.

	C	D	E
Engineering Hours:	3	5	2
Manufacturing Hours:	2	6	2
Tooling Hours:	1	8	1
Quality Assurance Hours:	1	8	1

4. Increasing the percentage of composites requiring hand lay-up.

	C	D	E
Engineering Hours:	10	1	
Manufacturing Hours:	2		9
Tooling Hours:	2	8	1
Quality Assurance Hours:	1	8	2

5. Increasing the size of composite parts.

	C	D	E
Engineering Hours:	10	1	
Manufacturing Hours:	3	7	1
Tooling Hours:	2	8	1
Quality Assurance Hours:	2	9	

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

6. Increasing the use of composites for purposes of low observability.

	C	D	E
Engineering Hours:	1	9	1
Manufacturing Hours:		9	2
Tooling Hours:		9	2
Quality Assurance Hours:		10	1

7. A fighter aircraft with 50% or more composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	2	5	4
Manufacturing Hours:	1	3	7
Tooling Hours:	1	6	4
Quality Assurance Hours:	2	6	3

8. A bomber aircraft with 50% or more composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	3	2	5
Manufacturing Hours:	1	2	7
Tooling Hours:	1	3	6
Quality Assurance Hours:	2	3	5

9. A cargo or tanker aircraft with 50% or more composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	4	3	3
Manufacturing Hours:	2	2	6
Tooling Hours:	1	5	4
Quality Assurance Hours:	2	5	3

10. [illegible] fighter aircraft with 50% or more composites and less than 50% of [illegible]es are complex in shape.

	C	D	E
Engineering Hours:	3	7	
Manufacturing Hours:	1	9	
Tooling Hours:	1	9	
Quality Assurance Hours:	2	8	

11. A bomber aircraft with 50% or more composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	3	6	
Manufacturing Hours:	1	8	
Tooling Hours:	1	8	
Quality Assurance Hours:	2	7	

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

12. A cargo or tanker aircraft with 50% or more composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	3	5	1
Manufacturing Hours:	2	7	
Tooling Hours:	2	7	
Quality Assurance Hours:	2	7	

13. A fighter aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	4	7	
Manufacturing Hours:	3	8	
Tooling Hours:	2	9	
Quality Assurance Hours:	3	8	

14. A bomber aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	4	6	
Manufacturing Hours:	3	7	
Tooling Hours:	2	8	
Quality Assurance Hours:	4	6	

15. A cargo or tanker aircraft with 25 to 50% composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	9	1	
Manufacturing Hours:	3	7	
Tooling Hours:	2	8	
Quality Assurance Hours:	7	3	

16. A fighter aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	9	2	
Manufacturing Hours:	4	7	
Tooling Hours:	4	7	
Quality Assurance Hours:	9	2	

17. A bomber aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	9	1	
Manufacturing Hours:	6	4	
Tooling Hours:	6	4	
Quality Assurance Hours:	9	1	

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

18. A cargo or tanker aircraft with 25 to 50% composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	9	1	
Manufacturing Hours:	7	3	
Tooling Hours:	7	3	
Quality Assurance Hours:	9	1	

19. A fighter aircraft with less than 25% composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	11		
Manufacturing Hours:	7	4	
Tooling Hours:	9	2	
Quality Assurance Hours:	10	1	

20. A bomber aircraft with less than 25% composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	10		
Manufacturing Hours:	6	4	
Tooling Hours:	8	2	
Quality Assurance Hours:	9	1	

21. A cargo or tanker aircraft with less than 25% composites and at least 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	10		
Manufacturing Hours:	7	3	
Tooling Hours:	9	1	
Quality Assurance Hours:	10		

22. A fighter aircraft with less than 25% composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	11		
Manufacturing Hours:	11		
Tooling Hours:	11		
Quality Assurance Hours:	11		

23. A bomber aircraft with less than 25% composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	10		
Manufacturing Hours:	10		
Tooling Hours:	10		
Quality Assurance Hours:	10		

C	D	E
1.0 to 1.5 Times More Hours	1.5 to 2.0 Times More Hours	More than 2.0 Times More Hours

24. A cargo or tanker aircraft with less than 25% composites and less than 50% of composites are complex in shape.

	C	D	E
Engineering Hours:	10		
Manufacturing Hours:	10		
Tooling Hours:	10		
Quality Assurance Hours:	10		

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13. ABSTRACT *(Maximum 200 words)*
This study provides a guide to cost analysts who must consider the impact of composite materials on airframe costs. A literature review was conducted to determine the availability of cost models which incorporate the effect of composites on cost. A number of models are available, but no individual model was found that is applicable for every situation. In order to provide a baseline upon which analysts can compare model results as well as provide guidance in selecting cost drivers, a Delphi survey was conducted. Questionnaire results indicate that composite weight (as a percentage of total weight), composite part complexity, percentage of composites in load-bearing roles, composite part size, fabrication technique, and percentage of composites in a low observable role are all potentially significant cost drivers. Delphi results also indicate that engineering and quality assurance labor hours are quite sensitive to composite weight, while manufacturing and tooling hours are more sensitive to composite part complexity. Finally, the Delphi results indicate that, although there are some differences in composite labor hour impacts across aircraft types, there are no discernable patterns to the differences.

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